STATISTICS AND MODELLING OF THE INFLUENCE OF THE VOLUME, FALL HEIGHT AND TOPOGRAPHY ON VOLCANIC DEBRIS AVALANCHE DEPOSITS

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Abstract

This research project on volcanic debris avalanches aims to provide a better understanding of the influence of the volume, fall height and topography on the deposit location and morphology. This will enable improvements in delineation of the areas at risk from volcanic debris avalanches, and improvements in management of a disaster should it occur. Undertaken to fulfil the requirements for a double degree (Geological Engineering and MSc in Hazard and Disaster Management) this work is the result of a collaboration between Polytechnic Institute LaSalle-Beauvais in France and the University of Canterbury in New Zealand. Following a brief introduction to the topic, statistical analyses of volcanic debris avalanche deposits are undertaken. Multiple variables analyses (Principal Components Analyses and Regressions) were carried out using a database of 298 volcanic debris avalanches derived from modification of Dufresne's recent database. It was found that the volume has the main influence on the deposits rather than the fall height; the latter seems to have greater effect on avalanches of small volume. The topography into which the deposit is emplaced mainly determines its geometrical characteristics. These statistical results were compared with the results of laboratory-scale analogue modelling. A model similar to that used by Shea in 2005 provided data indicating similar trends of the influence of volume, fall height and topography on mass movement deposits at all scales. The final aspect of this project was a numerical simulation of a large debris avalanche from the north flank of the Taranaki volcano in the direction of the city of New Plymouth. The numerical code *VolcFlow* developed by Kelfoun in 2005 was used, after being tested against the laboratory experiments to verity its accuracy. The simulations showed that the Pouaki range protects the city of New Plymouth form major impacts from Taranaki collapses, but also indicated some potential problems with the hazard zoning and evacuation zones presently in place.

Key-words: debris avalanche; volcano; volume; fall height; topography; statistical analyses; analogue modelling; numerical modelling; VolcFlow; Taranaki; New Plymouth .

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Introduction

People have always been fascinated by volcanoes because of their power, the danger they represent and the fact that they cannot be controlled. This fascination started very early in human history; the first known representation of a volcano is a painting of Mount Hasan (Turkey) made in about 6000 B.C. This fascination was not shown only by representing volcanoes in artistic ways, but also by trying to understand and explain volcanoes and their eruptions. However, even if most of the time these phenomena were associated with Gods and their manifestations (Fig. 1) and were supposed to be the result of divine anger or the manifestation of Satan (which is still the case in some tribes nowadays), some scientific theories were developed in order to try to explain it.

Figure 1. Illustrations of Gods representing volcanoes (Greek god Hephaestus & Hawaiian goddess Pelée)

As the years went by, ideas about volcanoes have changed and evolved, as has technology as well). For example in ancient times, Plato thought that the Earth was constituted of a vast river of fire which was at the origin of volcanoes. Aristotle thought that eruptions were the result of friction created by the wind in confined areas in the Earth. In a nutshell, until the XVI century, wind was the main parameter at the origin of eruption in most theories. The first true scientific reasoning in volcanology was that of the British ambassador William Hamilton in the mid-end of the XVIII century. His documentations and studies of eruptions of Vesuvius (Italy) and also Etna (Sicily, Italy) resulted in the publication of several books. A few years later, knowledge of volcanoes was improved in 1831 by the explanation of the formation of volcanoes proposed by Constant Prévost.

The science of volcanology as we know it today is called modern volcanology, and started in the XX century with the observation of the Montagne Pelée eruption (Martinique, France) in 1902 by Alfred Lacroix and the theory of the continental drift by Alfred Wegener in 1912.

Since this period many improvements have been made in knowledge and understanding volcanoes. However not everything has yet been discovered and lots of things remain to be found.

This is well illustrated by the knowledge of volcanic debris avalanches. This phenomenon was first observed and described in the field during the 1980 Mount St Helens eruption (Washington, USA), and many questions remain to be answered. This is an important factor in hazard and disaster management. Even if this phenomenon is quite rare at the human time-scale (approximately one of this size every hundred years), it is the most dangerous one. 90% of the deaths from a volcanic origin (250 000 persons of the 260 000 victims known since 1500 from composite volcanoes; Komorowski, 2003) are the result of volcanic debris avalanches.

This situation is not improved by the location of composite volcanoes capable of generating debris avalanches. As a matter of fact most of these volcanoes are close to big cities (for example Popocatepetl and Mexico City in Mexico); this means areas with high concentrations of people are at risk, which can be a problem in case of evacuation. To make things a little bit more difficult, most of these areas are in less economically developed countries. This means that they have not enough money to meet the cost of detection tools and the creation/maintenance of an observatory, to provide warning and advice. Added to these problems are cultural and religious differences which have an impact on the way in which scientific data are received by the population.

It is in this perspective of improving hazard and disaster management of such areas that this project started. The management of a hazard or a disaster is divided into several steps (communication, evacuation…) and is different depending on when it is done (before, during or after the disaster). It is common knowledge that the better the work is done before the disaster, the better it will be managed. One of the essential parameters of preparation and management of a disaster is to determine the area that might be affected by the hazard. *Prima facie* it seems logical that the area impacted by the debris avalanche is affected by different volumes of the debris avalanche and topographies of the environment. This is why this research project tries to answer the following questions:

Do the volume of the debris avalanche and its fall height have an impact on the runout of the deposit?

Does the topography of the environment have an impact on the extent of the debris avalanche deposit?

Is it possible to find relationships among the volume involved, the environment, the deposit runout and extent, from general tends found during this research; and are these applicable to any volcanic debris avalanche?

To try to answer these questions, this research has been divided in four main parts. The first aim, after an introduction to the phenomenon of volcanic debris avalanche (chapter I), is to determine if any general tends can be found by using field data collected all around the world by different scientists. This has been done by creating a database and doing statistical studies (chapter II) with different methods. However in order to test the trends found by the statistical studies, analogue and numerical modeling have also been done (chapter III). The aim was first to reduce as much as possible any error in the trends found by using several methods, then to test the accuracy of the *Volcflow* computer code created by Karim Kelfoun (Laboratoire des Volcans et Magmas, Clermont-Ferrand, France.) in modelling volcanic debris avalanches. The last thing done was a case study (chapter IV) in order to apply the results found to a real case. The area of New Plymouth and the Taranaki volcano (New Zealand) have been selected for this study. The north part of the volcano is of interest because of the location of the town (which is the most important town of the region) and also because of its particular topography due to its history (Fig. 2).

Figure 2. The town of New Plymouth & Taranaki volcano (Lloyd Homer)

Chapter 1. General knowledge of volcanic debris avalanches

Volcanoes are well-known for their powerful eruptions, which are also hazards. However, another hazard, less obvious but much often more catastrophic, is due to the inherent instability of the volcano's flank which can generate a massive landslide.

This hazard, called debris avalanche, was recognised, observed and understood for the first time after the 1980 eruption of the Mount St. Helens (Washington State, USA; Voight et al., 1983). Many years before that famous May 18th, deposits from the same kind of phenomena had often been interpreted as volcanic flows (Siebert, 1984). Nevertheless, some scientists (e.g. Nakamura, 1978) had started to think about volcano collapses as a special kind of event but none had ever been observed. The consequence of this observation was the sudden interest of the scientific community toward all these similar-looking deposits. As a result, their re-examination has greatly increased the number of volcanic debris avalanches known. Today, more than 300 volcanic debris avalanche deposits are recognised round the world.

The aim of this first chapter is to present a summary of the current knowledge of this phenomenon in order to demonstrate its complexity. A brief introduction to volcanic debris avalanches will be given, then the rupture zone will be described and the deposits characterised, before ending with a description of debris avalanche behaviour.

I. Volcanic debris avalanches

In order to introduce volcanic debris avalanches, we first define the phenomenon, and then the classifications used will be explained before introducing the nomenclature of the different elements.

I.1. Definition

A debris avalanche is a large, extremely mobile, gravity-driven, water-unsaturated volume of debris moving down a hillslope (Siebert, 1984, 1996; Glicken, 1996; Leyrit, 2000). Debris avalanches of different natures are derived from rock of different nature (volcanic or non-volcanic), and they can take place both in air and below the sea. This phenomenon is the result of destabilization of a volcanic cone (Ui, 1983; Siebert, 1984). It is initially a slide which turns quickly into a flow that can travel huge distances (up to 120km for the debris avalanche of the Nevado de Colima volcano in Mexico) with high velocities (Voight et al., 1983; Glicken, 1991).

I.2. Classifications

As soon as volcanic debris avalanches were recognised, scientists integrated them into gravity-driven-landslide classifications.

<table>
<tr><th colspan="3" rowspan="3">Kind of movement</th><th colspan="3">Kind of material</th></tr>
<tr><th rowspan="2">Rock</th><th colspan="2">Soil</th></tr>
<tr><th>Coarse
(<80% sand and finer)</th><th>Fine
(>80% sand and finer)</th></tr>
<tr><td colspan="3">Fall</td><td>Rock fall</td><td>Debris fall</td><td>Earth fall</td></tr>
<tr><td colspan="3">Topple</td><td>Rock topple</td><td>Debris topple</td><td>Earth topple</td></tr>
<tr><td rowspan="3">Slide</td><td>Slump</td><td rowspan="2">Few units</td><td>Rock slump</td><td>Debris slump</td><td>Earth slump</td></tr>
<tr><td rowspan="2">Slide</td><td>Rock block slide</td><td>Debris block slide</td><td>Earth block slide</td></tr>
<tr><td>Several units</td><td>Rock slide</td><td>Debris slide</td><td>Earth slide</td></tr>
<tr><td colspan="3">Spread</td><td>Rock spread</td><td>Debris spread</td><td>Earth spread</td></tr>
<tr><td colspan="3">Flow</td><td>Rock flow</td><td>Debris flow</td><td>Earth flow</td></tr>
<tr><td colspan="3">Complex</td><td colspan="3">Combination of one or more kind of movement</td></tr>
</table>

Table 1. Landslide classification (modified from Varnes, 1978)

In the classification of Varnes (1978) which considers only the initial phase of the event, volcanic debris avalanche is a complex kind of movement (Table 1). It is also part of the epivolcanic phenomena which comprise debris avalanches and debris flows. The difference between these two phenomena is primarily the size and degree of saturation (Voight et al., 1981). A classification more specific to volcanic debris avalanches has been proposed by Siebert (1984); this is based on the parameters at the origin of the avalanche. This classification comprises three main types: type Bezymianny (Russia)-St Helens (USA), type Bandaï San (Japan) and type Unzen (Japan). This classification is less used now because of the fact that the phenomenon is complex and not enough parameters are used in this classification.

I.3. Nomenclature

The vocabulary used in this report has been classified in four different units.

I.3.1. Volcano and deposit

Stratovolcano: is a steep-sided volcano constructed of alternating layers of lava flows and pyroclastic material such as volcanic ash (McDonald, 1972).

Volcanic debris avalanche deposit: is a coarse-grained, poorly sorted, partially or entirely volcanic breccia with a grain size from clay to metric blocks (Siebert, 1984). Sedimentary criteria allow it to be differentiated from other volcanic breccias (Ui, 1983; Glicken, 1991), such as the usually hummocky surface morphology.

I.3.2. Rupture zone

Amphitheatre: is an arm-chair-shaped landscape feature formed at the source of a sector collapse. Characteristics of an amphitheatre such as the depth, width and height are variable (Ui et al., 2000).

Sector collapse: is a large-scale gravity-driven destructive volcanic process which produces a debris avalanche (Ui et al., 2000). It is caused by the interaction of two different mechanisms: a weakening one and a triggering one.

I.3.3. Granulometry

Clast: a rock of any size that would not break if passed through a sieve or immersed in water (Glicken, 1996).

Megablock: is a relatively coherent piece of the source volcano, which can be fractured and deformed (Glicken, 1996). The size of a megablock can range from a meter to more than several hundred meters across.

Block: is a relatively coherent element of heterogeneous nature usually of centimeter scale.

Matrix: is a unit of heterogeneous finer-grained (sandy-silty size) interclast material (Siebert, 1996; Leyrit, 2000). This usually completely disorganized unit is found between coarser elements.

I.3.4. Characteristic elements of the deposit

Hummock: is a characteristic topographic feature for debris avalanche deposits. It is a small hill which is variable and irregular in shape (Ui et al., 2000).

Jigsaw crack: is a characteristic joint pattern within debris avalanche megablocks and blocks. It is typically more irregular than the cooling joints of massive igneous rocks. The joint planes usually remain closed. However once they are open wide, due to deformation during the transport of the debris avalanche, they are called jigsaw fits (Ui et al., 2000).

II. Description of the rupture zone

In order to understand a phenomenon, it is crucial to study its origin. In fact, depending on the source, the deposits coming from it will be different. As the rupture zone is characterised by its shape, it will be first explored, and then the parameters determining the instability will be introduced before giving some historical examples.

II.1. Scarp characteristics

The scarp, also called avalanche caldera, is an open depression on one side of an edifice characterised by steep slopes (Fig.3). The size of the caldera varies but is on average between one and three kilometres (Siebert, 1984, 1996), such that the opening angle is on average between 20° and 30° (Francis and Wells, 1988).

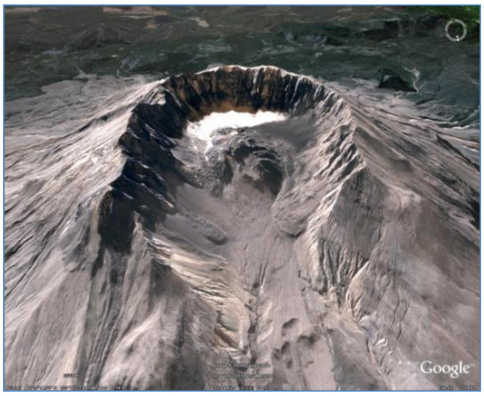


Figure 3. Avalanche caldera of Mount St Helens volcano, USA (From Google Earth, 2007); it is partly infilled by subsequent dome-building

The caldera is usually amphitheatre-shaped. This shape, which can be accentuated by directed explosive activity (blast) during the collapse, determines the volume involved in the phenomenon (Komorowski, 2003). However, a caldera can be the origin of several collapses (such as the Shiveluch volcano in Russia; Ponomareva et al., 2006) and filled by volcanic materials (such as lava flow, dome and volcanoclastic products) and/or by sedimentary materials (Ui, 1983). Bernard (2008) showed that some distinct caldera shapes can be distinguished, giving a classification with seven shapes based on profile and plan (Fig.4).

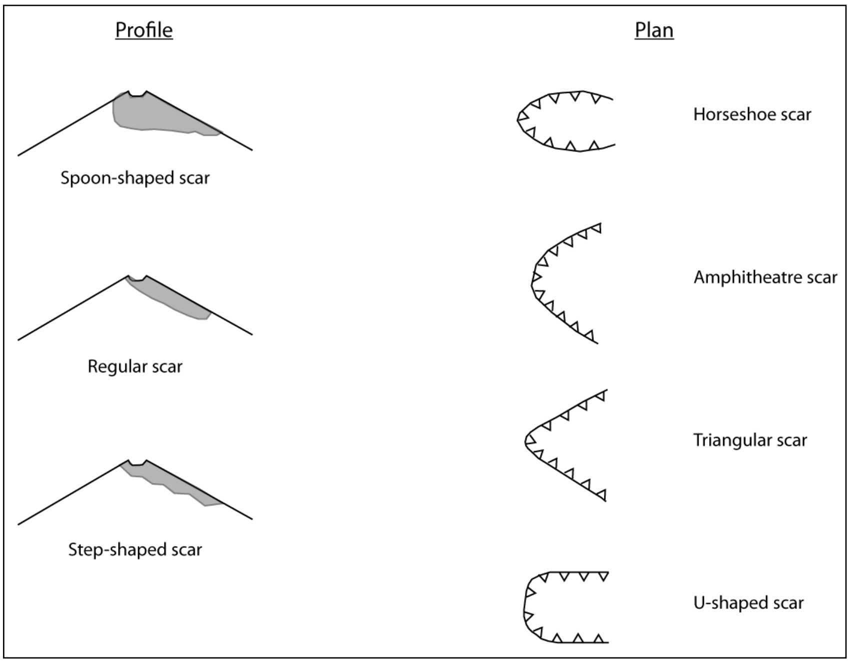


Figure 4. Scar shape classification (Modified from Bernard, 2008)

The difference between avalanche calderas and other events is essentially morphological. For example, collapse calderas do not have an open side (such as Toba volcano in Sumatra) and glacial cirques are less deep and sometimes characterised by frontal and lateral tills (Siebert, 1984; Karátson et al, 1999).

II.2. Parameters determining volcanic cone instability and collapse

An analogy can be proposed between debris avalanche and fire in terms of the parameters determining the phenomenon. A fire is supported by the presence of combustibles (furniture, fuel, etc) and a combustive (in general oxygen in the air). The phenomenon will not happen if there is no activation energy (such as sparks for the example of fire). Once initiated, the phenomenon is self-sustaining.

It is important at the start to differentiate parameters of the strength of the volcano and those responsible for triggering the phenomenon. The presence of both parameters at appropriate relative intensities will cause a collapse and avalanche.

II.2.1. Collapse parameters: fragility

Several parameters, acting over different time-scales, can cause volcanic cone instability (Fig.5).

The nature of the edifice materials can influence the stability of the volcano. For instance a volcano with layers of different natures, such as a stratovolcano, is more sensitive than a homogeneous edifice to a collapse due to the weakness of some layers (Siebert, 1996). The composition of the substratum has also an impact. For example, a substratum made of clay is likely place for landslide (Siebert, 1996). Recent researches have also pointed out that a rapid change of the composition of the magma and hence of the eruptive style might affect the stability of the volcano (Robin et al., 1997).

The morphology also has an impact because of the irregular shape that affects the centre of gravity of the edifice. This can be the result of an asymmetric shape due to intrusions such as dike, sill or endogeneous dome (Voight et al., 1981; McGuire, 1996), and can be increased by erosion (Carrasco-Núñez et al., 2006). A volcanic edifice with steep slopes and also a sloping substratum can contribute to the collapse (Voight and Elsworth, 1997). In fact the steeper the slope, the easier the destabilisation will be.

Chemical and physical properties affect the stability of the volcanic edifice. Chemistry by the fluid/rock interaction modifies the rock resistance through a decrease of the cohesion. For example a slide will be more likely if there are fragile materials such as volcanic material turning into clay due to chemical changes by hydrothermal fluids circulation (Lopez and Williams, 1993; McGuire, 2003; Reid, 2004). Another example is the salinity and/or sea level variation that can cause a modification of the pore pressure which can increase the destabilisation of an island volcano (Day, 1996; McGuire, 1996). Physical properties are no less important than chemical ones. Fracture networks (Siebe et al., 1992; Vidal, 1998) and brecciation processes (McGuire, 1996) also contribute to the weakness of the edifice.

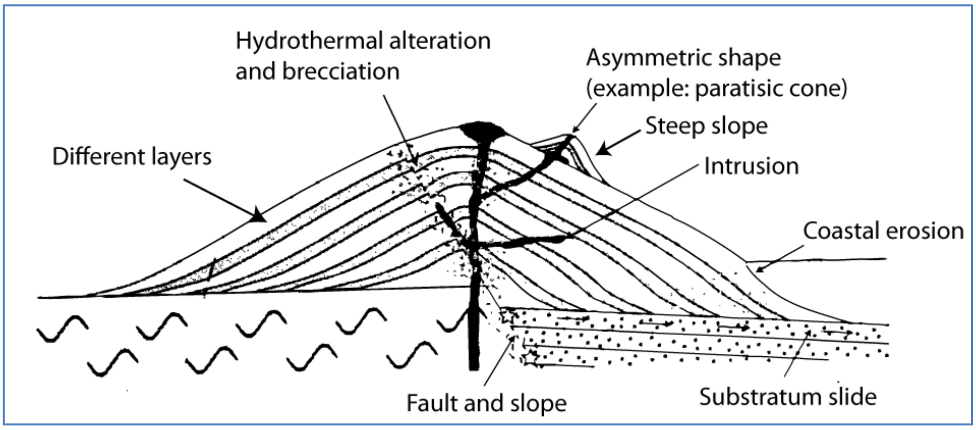


Figure 5. Illustration of the parameters at the origin of the instability of the volcano (modified from McGuire, 1996)

II.2.2. Parameters triggering the collapse

Parameters responsible for the strength of the volcano are not the only ones to cause a collapse (Fig.6). Often there is also a triggering parameter which activates the slide if the instability parameters are appropriate. Three main different types of triggering parameters have been recognized (Siebert et al., 1987).

- Seismic activity can on its own destabilize the edifice and causes pore pressure modifications by shaking (Siebert et al., 1987).
- Volcanic activity, which is the obvious origin of collapses, can be of different styles and also accompanied by seismic activity (Voight and Elsworth, 1997).
- Climatic events such as hurricanes or heavy rain falls (McGuire, 1996) or melt of a summit glacier (Reid, 2004) can trigger the collapse. In fact, any increase of water saturation will decrease the strength of the edifice.

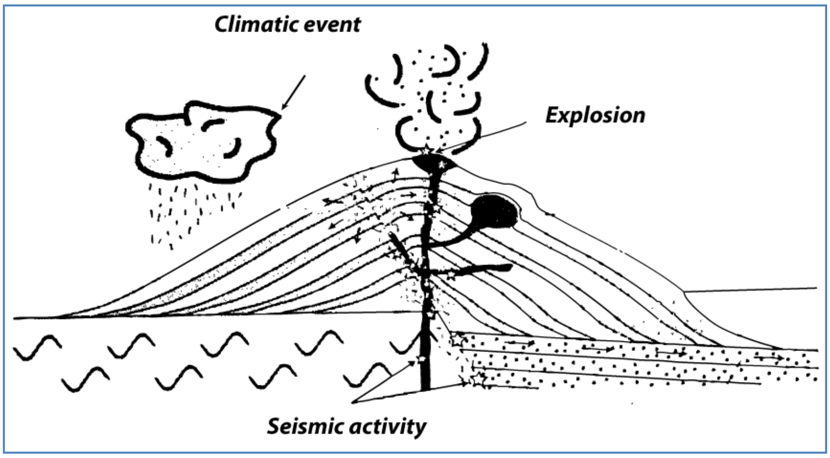


Figure 6. Illustration of parameters triggering the collapse (modified from McGuire, 1996)

III. Deposit characteristics

Deposits are the result of collapse and runout and are located at or close to the foot of the volcano. They are, most of the time, excellent criteria for identification because of their good preservation (Leyrit, 2000). The shape and dimensions of these deposits will be first introduced before explaining the different facies and then their structures.

III.1. Dimensions and shape

The dimension and shape of a deposit can be quantified by aerial photos and/or satellite images if the deposit is still quite fresh; otherwise work field is needed (Francis and Wells, 1988).

III.1.1. Dimensions

Dimensions vary greatly from one debris avalanche deposit to another but are quite important. Six different parameters are used to characterise the dimensions of the deposit: the surface area (A_D), the length (L_D), the width (W_D), the perimeter (P_D), the thickness (T_D) and the surface inclination (α_D). As a result the volume of the deposit (V_D) can be calculated. However, it is reliable only if the measurement is done very carefully with the same method each time and if the error margin is kept in mind.

III.1.2. Shape

Shape of the deposit has not been very well studied; moreover it has been shown that the environment of the volcano has an impact on the shape of the deposit. For example, a deposit will be spread out across a plain area whereas it will be narrowed in valleys (Palmer et al., 1991). A classification of six main shapes for the deposit has been created from the observation of aerial views of different deposits (Bernard, 2008; Fig.7).

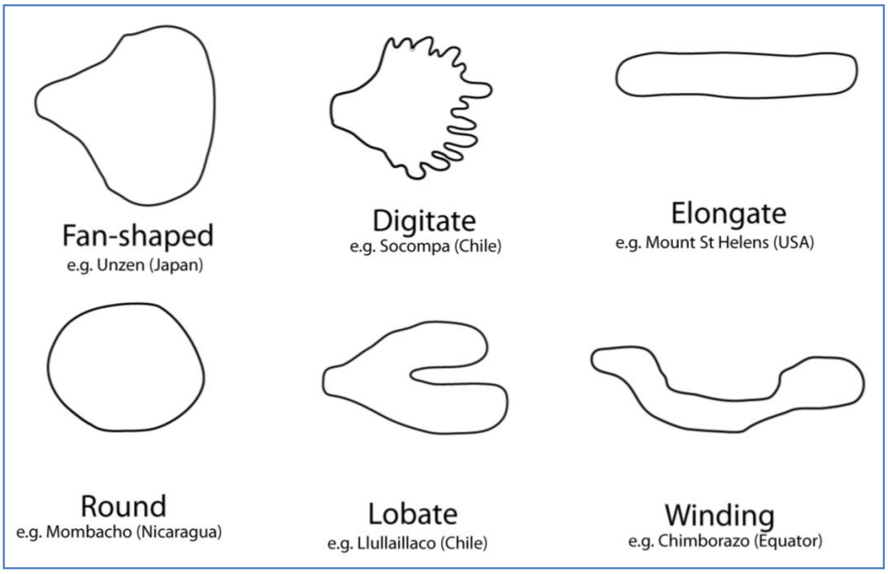


Figure 7. Classification of the deposit based on its shape (modified from Bernard, 2008)

III.2. Facies of the deposits

In general, debris avalanche deposits are angular breccias with an extremely variable grain size (from megablocks to clay) without any stratification or sorting. However, based on morphological, lithological and sedimentary features, two main facies have been identified: block facies and mixed facies (Ui, 1983; Siebert, 1984; Glicken 1991; Palmer et al., 1991). It is possible to identify several other facies within these two main classes that will be described.

III.2.1. Block facies

This facies is characterised by a chaotic stack of several blocks and megablocks on top of the others (Fig.8). These materials are massive and usually fractured with a lithological homogeneity (Palmer et al., 1991; Larger, 1999). It is quite difficult to differentiate each block from the other because limits are not distinct. However, three types of megablocks haven been identified: coherent ones, more or less consolidated breccias, and panels with the original stratification (Leyrit, 2000). These segments (blocks and megablocks) are transported relatively intact from the volcano and mostly dominate this facies (more than 70% by volume whereas inter-block matrix represents less than 30% (Palmer et al., 1991; Pouget and Tixerand, 2008).

Figure 8. Block facies at the Pialottes, debris avalanche of the Cère valley, Cantal, France.

III.2.2. Mixed facies

The mixed facies has a larger proportion of matrix (between 30 and 90%) than the block facies (Palmer et al., 1991; Pouget and Tixerand, 2008; Fig.9). Megaclasts are rarer and smaller. The origin of the particles from lithic clasts is the fragmentation of a part of the former edifice. However, it is possible to find locally fragments of secondary origin (wood, earth, substratum rocks, etc). These secondary elements are the result of incorporation during debris avalanche displacement.

Figure 9. Mixed facies near the fall of the Roucolle, debris avalanche of the Cère valley, Cantal, France

III.2.3. Relation between these two facies

Several studies have shown that the greater the distance from the source, the greater is the proportion of matrix in the deposit (Vidal et al., 1996). These results from the decrease of the percentage of block facies and increase of the percentage of the mixed facies as the distance from the failure origin increases (Ui and Glicken, 1986; Glicken, 1996). However, there are no distinct boundaries between these two facies in the deposit, the facies changes slowly (over a few kilometres; Pouget and Tixerand, 2008) and this transition is known as an intermediate facies (Palmer et al., 1991). As a result there is a reduction of the size of the clasts (Ui and Glicken, 1986) and an increase of the proportion of secondary elements in the deposit with increasing runout (Palmer et al., 1991). In summary, block facies is present in the proximal zone, whereas mixed facies dominate the distal zone, but either of these facies can be missing. However, debris avalanche deposit can turn into a lahar deposit if the proportion of water increases (Palmer et al., 1991).

III.3. Structures

Structures are also characteristic features of the deposits, and can differ from one facies to another. Of course, they can be the result of different processes: due to the nature of the deposit or to the growth of the volcano, or to the debris avalanche process (collapse and transport) or to subsequent events (landslide, tectonic, etc; Bernard, 2008). Only structures due to debris avalanche process itself will be described in this part.

III.3.1. Base of the deposit

Debris avalanches are often believed to be very erosive (Yarnold, 1993). This is not only because of the incorporation of secondary materials; the presence of folding, boudinage and material injected into megablocks or substratum is also an argument in favour of that process (Schneider and Fisher, 1998). However, these deformations are not all visible everywhere in the deposit. They are present more often at the base of the deposit, especially under megablocks. Depending on the base, it is possible to find crushed materials forced into a crystalline substratum (Schneider and Fisher, 1998) or alignments of millimetric materials at the wall of the injection (Fig.10).

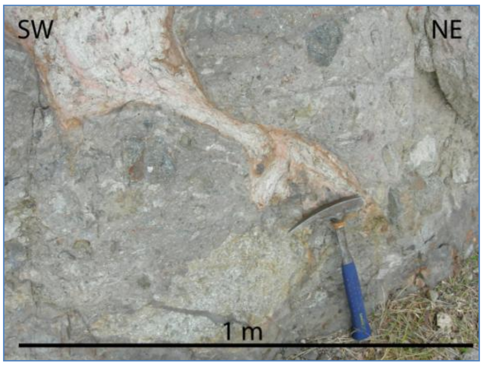


Figure 10. Example of injection at the base of Laprade of the Jordanne valley, Cantal, France

III.3.2. Internal structures

Jigsaw cracking is a typical structure of debris avalanche deposits (Ui, 1983). It is a radial fracture pattern or an irregular fracture network in which the displacement is very small so it is possible to visually refit the pieces (Siebert, 1996). In the terminology of rock avalanches these are known as "shattered undisaggregated clasts". Glicken (1996) interpreted jigsaw cracking as the result of a small dilatation of the volume of the blocks without disaggregation. However, the displacement is more important in the distal zone than the proximal (Ui and Glicken, 1986), and the resultant slight disaggregation is then called jigsaw fit instead of jigsaw cracks. Jigsaws are different from cooling joints by being less smooth and flat (Ui, 1983). These structures are visible at both macroscopic and microscopic scales in the deposit (Komorowski et al., 1991; Pouget and Tixerand, 2008; Fig.11).

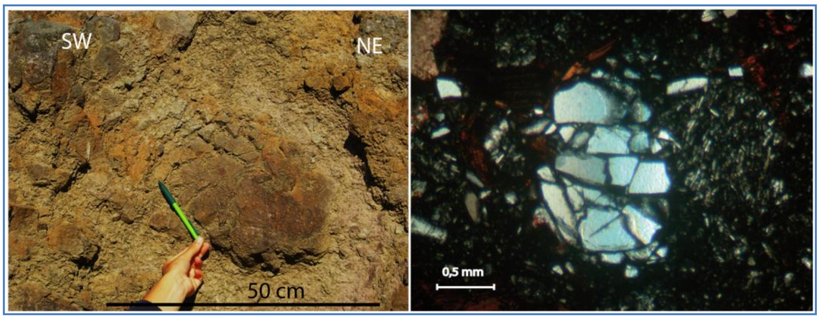


Figure 11. Example of macroscopic and microscopic jigsaw cracks from the debris avalanche deposit of the Cère Valley, Cantal, France

Some authors have also shown that it is possible to have a mix of matrix materials of different nature (Siebert, 1984; Dahy and Hubert, 2008), but this is not universal.

III.3.3. External structure: deposit morphology

As the facies are not the same from the proximal to the distal zones, and as they have specific characteristics, the surface morphology of the deposit also changes with distance from the source. The block facies has an uneven surface due to the presence and concentration of hummocks (Crandell, 1989; Palmer et al., 1991). This hummocky topography is very characteristic of debris avalanche deposits (Siebert, 1984). Hummocks can have different shapes (conical; Siebert, 1984; rounded; Crandell et al., 1984; or ridges: length is greater than width; Ui et al., 2000) and have been classified in three main types by Glicken (1991) (A: from the block facies, B: from the mixed facies, C: due to blocks into the mixed facies; Fig.12). Alignments of hummocks can be observed as a result of their properties (strong and competent; Dufresne and Davies, 2009) and if the velocity of the flow is not too high relative to the velocity component perpendicular to the flow. However, not all kinds of hummocks are always present in a deposit and ridges can dominate (Francis and Wells, 1988). By contrast, mixed facies is characterised by a flatter surface morphology which can have occasional hummocks (Glicken, 1991).

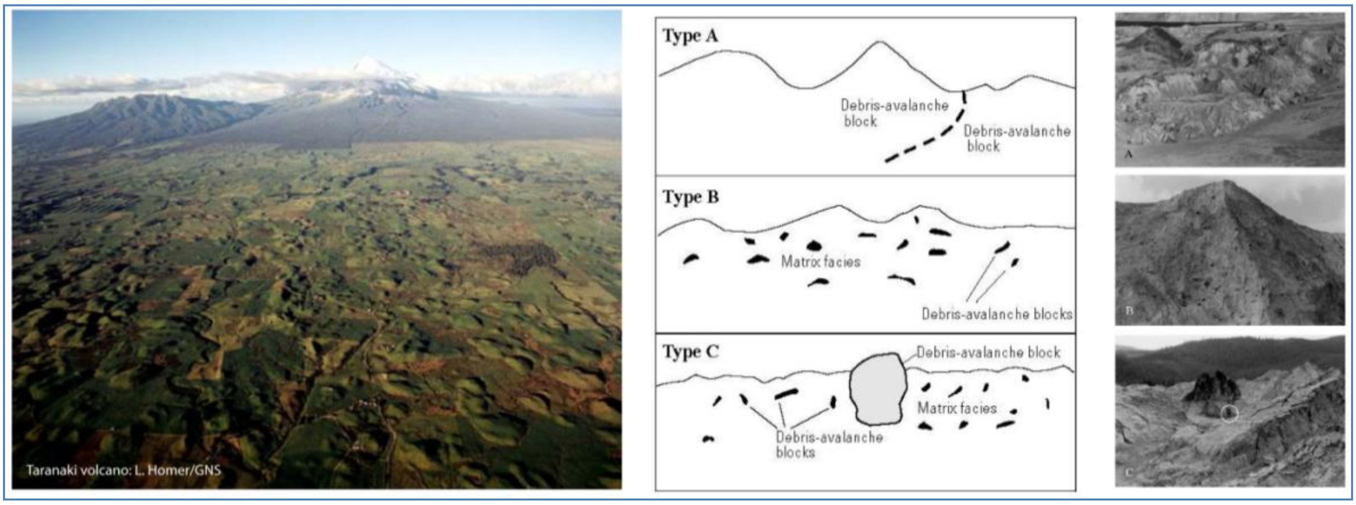


Figure 12. Example of hummock from Taranaki volcano, New Zealand and illustration of the types of hummocks (Glicken, 1996)

The deposit is also sometimes characterised by the presence of marginal levees and a frontal lobe (Crandell et al., 1988) which are good criteria to distinguish them from mudflow deposits (Siebert, 1996) and are the result of a lower flow velocity (reducing to zero) at the margins (Glicken, 1996).

IV. Behaviour of debris avalanches

The behaviour of debris avalanches has been described in detail from the rupture zone to the deposit. However, this behaviour has not been fully explained yet. This section will present the present state of knowledge regarding the formation of the deposit, the mobility of the event and also the influence of topography on emplacement.

IV.1. Formation: from collapse to deposit

The debris avalanche of Mount St Helens was the first event of this type studied in sufficient detail to provide information on the different stages of formation of the deposit. These three main phases have been identified with the help of the photography of Gary Rosenquist of the Mount St Helens collapse in 1980 (Voight, 1981; Fig.13). The first phase is the collapse of the edifice which is the beginning of the rockslide; as a result the materials start moving, initially as a coherent block but with increasing disaggregation. Then the landslide turns into a flow once the rocks are sufficiently brecciated (Leyrit, 2000). This second phase is composed of mobile debris and is called the flow phase. Then the last phase called the deposit phase which starts once the flow has lost energy and decelerates to rest.

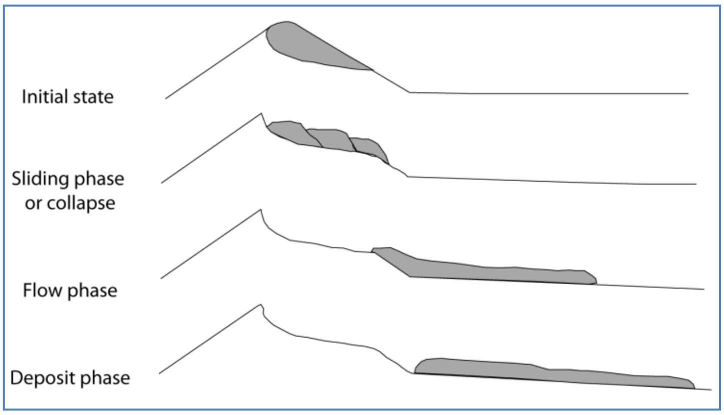


Figure 13. The main stages of a debris avalanche (modified from Bernard, 2008)

IV.2. Mobility

It is well known that large volcanic debris avalanches travel a surprisingly long distance. Hsü (1975) used the Coulomb friction law (which is the following relation between the distance (L), the height (L) and the angle of the slope with the horizon (α):

$$H = \tan(\alpha) . L$$

This relation between distance and height is called the apparent friction coefficient (µ). This coefficient quantifies the mobility of the event, and distinguishes between volcanic and non volcanic debris avalanches. Siebert, (1984) showed that volcanic debris avalanches travel farther than non volcanic debris avalanches relative to the height of fall .

Several theories have tried to explain this extreme mobility and the way volcanic debris avalanches behave, but for the moment none of these theories explains everything and is entirely accepted by the scientific community. However, several researchers agree on the fact that debris avalanche behaviour cannot be described by simple frictional models (Kelfoun and Duitt, 2005; Crosta et al., in press; Davies et al., 2010). One of the theories is based on the dynamic rock fragmentation that occurs in the basal region (Davies et al, 2010). It is the result of the deformation of particles (even if smaller ones are less likely to be affected by this process than biggest ones) which creates new fracture surfaces and releases kinetic energy that reduces the frictional resistance and increases the mobility (Davies and McSaveney, 2009). This theory matches the result of the numerical modelling of the Socompa event (Kelfoun and Duitt, 2005) which used a low and constant basal resistance (Kelfoun and Duitt, 2005; Davies et al, 2010). However more experimental works must be done in order to extend this theory to other debris avalanches (Davies et al, 2010). There might be several reasons for the beginning of the deposit process but the topography of the environment must be one of those.

IV.3. Morphology of the environment

The topography of the environment has an effect on the shape of the deposit (e.g. III.1.2). Deposits tend to be spread out when the topography near to the volcano does not confine them laterally. This might be due to the fact that the basal contact surface is then more important and so is the friction (Palmer et al., 1991; Fig.14). However in a confined area, the amount of matrix is more important and the size of megablocks is smaller (Takarada et al., 1999). Nevertheless, few studies have considered this effect which seems to be important for the shape and the thickness of the deposit. For example, analogue modelling has shown that the steeper the slope of the environment, the less thick a deposit is (Martinelli, 2005).

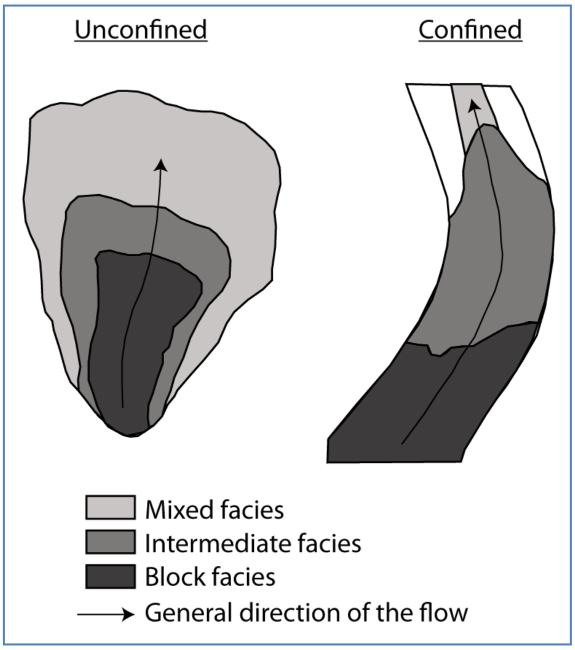


Figure 14. Influence of the morphology of the environment (modified from Palmer et al., 1991)

V. Historical events examples

We now briefly outline some historical volcanic debris avalanche events in order to illustrate this phenomenon.

V.1. Mount St Helens

On May 18th, 1980, Mount St Helens (Washington, USA) experienced the well-known debris avalanche which was the result of the collapse of 2.3km^3 of material of the northern flank (Glicken, 1996). This event occurred after two months of seismic activity and deformation of the volcano. It might have been started by a M = 5 seismic event (Stoffel and Stoffel, 1980) which was followed a few seconds later by the collapse of 8.5% of the edifice (Siebert et al., 1995), accompanied by a blast and a Plinian eruption. This left the horseshoe-shaped caldera of the volcano.

V.2. Bandai

On July 15th, 1888, a phreatic eruption occurred at Bandai-san (Japan). It was followed by a 1.5 km^3 debris avalanche due to the collapse of the north flank of the volcano (Siebert et al., 1987). This event did not involve juvenile material (Nakamura, 1978) but was accompanied with a blast. This event seems to be the result of a series of strong earthquakes and a phreatic eruption (Yamamoto et al., 1999).

V.3. Shieveluch

On November 12th, 1964, a Plinian eruption occurred at Shieveluch (Kamchatka, Russia) and was followed by the collapse of the southern sector of the volcano. The collapse was not followed by a blast which indicates that there was no crytodome (Belousov, 1995). As a result, a debris avalanche of volume 1.5km^3 of was created. The debris avalanche was not the first one from this andesitic volcano; at least 12 debris avalanches have occurred on the southern slope and two on the western slope (Ponomareva et al., 1998).

V.4. Socompa

Approximately 7000 years ago, the failure of the north-western flank of the Socompa volcano in Chile caused a debris avalanche. As a result a volume of 26km^3 of debris and 11km^3 of large slide blocks was created (Wadge et al., 1995). This event, which was identified as a debris avalanche in 1985, was followed by an eruption of pumiceous pyroclastic flow (Francis et al., 1985). The collapse at the origin of the debris avalanche, which covered over a distance of 40km and an area of 500 km^2 (Francis et al., 1985), appears to be the result of a gravitational collapse on an active thrust-anticlines in the sediments underlying the volcano (van Wyk de Vries et al., 2001).

To summarize, a debris avalanche is an epivolcanic phenomena produced by the sudden destabilisation of a volcano flank (Fig.15). It is a rapid gravity-driven mass movement which differs from debris flows in that it is much larger, not water-saturated and the load is entirely supported by particle-particle interaction (Siebert, 1984; Vallance, 2000). It is highly heterogeneous and not always associated with an eruption, so it is not a pyroclastic flow. It is characterised by two main facies (block, matrix) and topographic features such as a rupture scar and hummocky topography at the surface of the deposit (Ui et al., 2000).

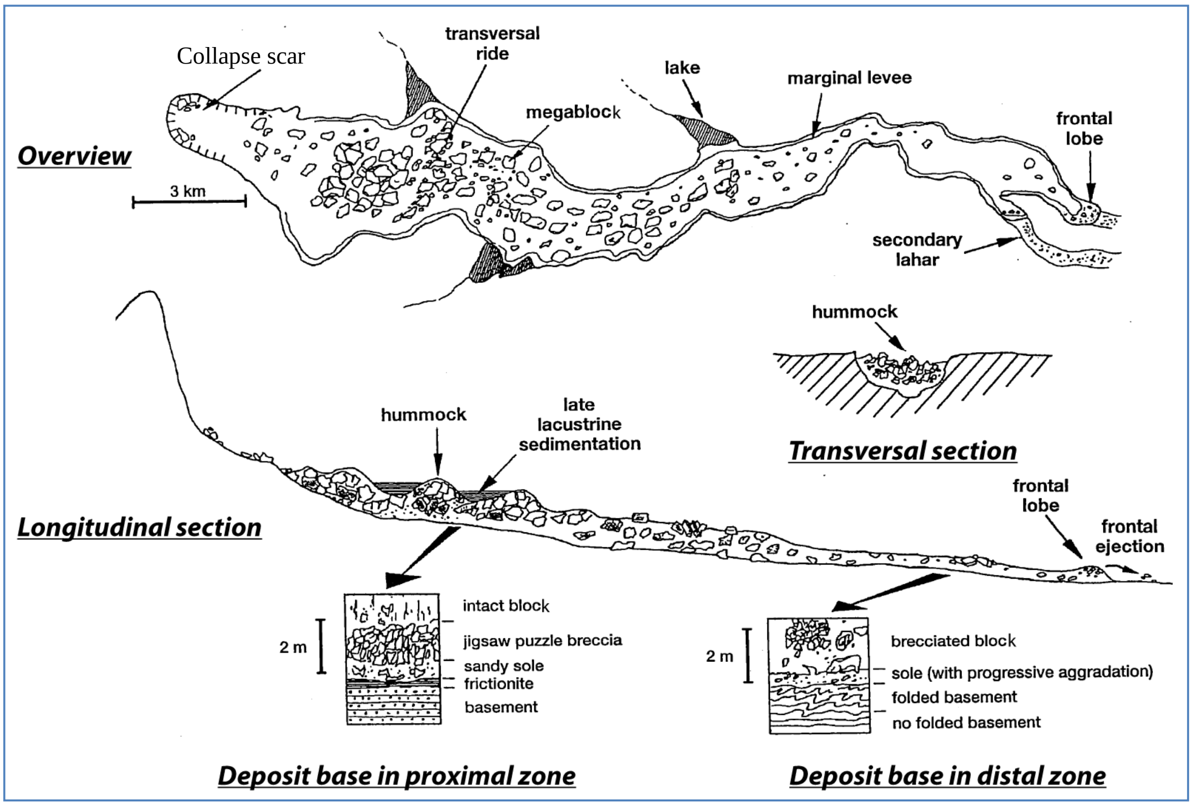


Figure 15. Synthetic illustration with the principal morphological, lithological and geometrical characteristics of rupture zones and deposit of debris avalanches (modified from Leyrit, 2000)

Now we look at the influence of the topography and the volume involved on the deposits of volcanic debris avalanches. Data from volcanoes all around the world from different authors have been used for a statistical analysis in order to see if general tends are present in field data.

Chapter 2. Statistical studies

Statistics is the use of mathematical tools to determine and characterize a set of data. The statistician John Wilder Tukey (1915-2000) suggested two main uses of statistics: the exploratory statistic which is used to obtain some qualitative idea regarding the properties; and the confirmatory statistic which is used to test some hypothesis. In this study both approaches are used.

The aim of this chapter is to understand the relations between different parameters of volcanic debris avalanche deposits and to deduce the importance of these relations. To do so, the database is first described, and then statistical analysis is carried out.

I. Database

For the last few years the idea of creating a general database of volcanic and non-volcanic debris avalanche deposits has been discussed. Finally in 2009, a first global database was developed; this database is first introduced before explaining the data selected for the present study.

I.1. Main database

The database used for this study has been created from Anja Dufresne's database with was part of her Ph.D. research project (Dufresne, 2009). Her database will now be explained and data selected to build the database for this study.

I.1.1. Introduction to the database

The main database is composed of 75% volcanic debris avalanches and 25% non-volcanic debris avalanches. It represents 225 volcanoes with a total of 298 volcanic debris avalanche deposits and a total of 105 non-volcanic debris avalanche deposits. 272 potential volcanic debris avalanches (92% of the volcanic debris avalanches in the database) have also been listed but not described. The aim of this database is to document all the debris-avalanche data known today, and published in the literature. It has been created in *Microsoft Excel* and is now maintained by V.O.G.R.I.P.A (Volcano Global Risk Identification and Analysis).

I.1.2. Database parameters

This database comprises 15 main categories which regroup several parameters. General information about the volcano (name, country, type, localisation ...) and the setting (climate, tectonic plate...) is given. However the main categories comprise details of the deposit and the collapse zone. Five groups describe the deposit: general knowledge (name, age...), statistics (volume, mobility...), morphology (hummocks, ridges...), shape (geometrical information) and the internal deposit structures (for example jigsaw features). Information about the substrate (nature, sediment affected by the avalanche...) and the collapse scar (length, depth...) are also provided in the database. Once all these important detailed are described the hazard aspect is addressed by considering the associated deposits, the fatalities and the population living at different distances from the volcano. As some information might not be part of the main groups defined before, a special additional note category was created in the database, such as a list of different links regarding the avalanche (website, PDF files, maps...). The last field is very important because it deals with the updated status of the database. It is the only way to have historical record of any update that could have been made by anyone.

I.1.3. Database problems and improvements

This database is the first one to be developed, and as with every first thing to be done there are some problems, and some improvements can be made. The main problem, which is not due to the way the database was created, is that there is no universal agreement on the way of measuring parameters. This implies that the error margin is not the same for every item, which creates the potential for further error. This problem can be corrected only once a field protocol finds general acceptance and new field studies are carried out.

Another problem for any statistical analysis between different debris avalanches is that the proportions of aerial, submarine, volcanic and/or rock debris avalanches are not equal. This difference will cause incorrect comparisons between these different phenomena because some are less represented than others. This problem will be less important once the database is updated with new studies, especially with the new submarine ones (e.g. Le Friant et al, 2001; 2008).

Some improvements can be made to the format of the database. *Microsoft Excel* is not the best tool in which to build a database, especially if the aim is that it can be updated by anyone. *Microsoft Access* allows better correlation between the information and a faster way of searching the information. It is also a good way to present the information and to update it easily by using forms. This is actually the next step of the team of the Washington Smithsonian Institute in charge of the database, who, once it is transferred to *Microsoft Access*, will put it online so that any scientist can see it, use it, update it and be in contact with those who have studied the deposits.

I.2. Database of this study

As this study is focused specifically on the impact of the volume and environment on the deposit morphology, the original database has been modified and also updated with new references and data.

I.2.1. Methodology

The first step was to create the new database, which means to determine the parameters necessary for the study and the general framework of the database. Thus some parameters from the original database have been ignored because they were not useful for the study; however 15 parameters have been conserved. Then data were entered. First all the volcanic debris avalanches from the original database were imported into this new database and the parameters were completed as much as possible; if some of them were still too poor in data then they were deleted from the database. 15 new debris avalanches deposits have been added from the recent literature.

The second step was to complete the field of the five new parameters: identification code, morphology of the environment, slope of the drop zone, slope of the deposit zone and the distance of transformation if the debris avalanche has transformed into a lahar. The identification code allows rapid identification of the event, as the same volcano can produce several debris avalanches. This code is composed of the two first letters of the name of the volcano, then the international abbreviation of the country and the number of the deposit of the volcano (numbered from the chronological order of publication). For example, for the first debris avalanche in the database from the Acatenango volcano, the code will be ***ACG1***. However if the letters are the same for two different volcanoes, the second vowel of the volcano's name will be added in lower case before the letter of the country, for example for Kambalny and Kamen' volcanoes in Kamchatka, the identification code will be ***KAaK1*** and ***KAeK1***.

Three new parameters are the morphology of the environment, the slope angle of the drop zone (α_1) and the slope angle of the deposit zone (α_2). The first is a qualitative morphological parameter whereas α_1 and α_2 are quantitative parameters. The morphological type of the environment has been classified through the literature and observation on maps and *Google Earth* (Fig.16).

Unconfined	Semi-confined		Confined			
Plain	One side	Some kilometers	Basin	River bed	Valley	Canyon

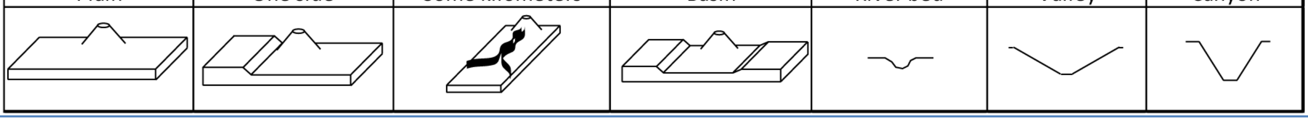
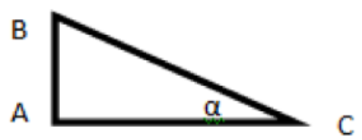


Figure 16. Classification of the morphology of the environment with examples

The quantitative slope parameters have been determined by using geological and topographic maps, published papers and *Google Earth*. If the distance of the collapse and the deposit areas were not given in the paper, they were measured on the geological map or the field map of the paper. Then the heights of drop and of the deposit zone were considered with the map or *Google Earth*. Then the inclination to the horizontal of the area selected was calculated (Fig.17).



$$\tan \propto = \frac{AB}{AC}$$

Figure 17. Illustration of the calcul of the angle

Of course some errors are present in these parameters, for example, volume, area, height and runout have not been calculated in the same way for all the deposits. Another error is that the angles have been calculated assuming that the slope was uniform over the area selected. In addition, if the original topography is not known, it has been assumed that the thickness of the deposit is uniform - which is known to be untrue, but is the simplest assumption.

I.2.2. Database

For this study 87 volcanoes comprise the database with a total of 119 debris avalanche deposits. Only 90 events have been selected because of lack of minimum information available. These debris avalanches occurred in all parts of the world, although American and Asiatic deposits are best represented in this database (89%; Tab.2). This repartition of the debris avalanche events highlights the Pacific Ring of Fire.

Continent	*Africa*	*America*	*Antarctica*	*Asia*	*Europe*	*Pacific*
%	6	38	1	51	1	3

Table 2. Location of debris avalanche deposits

Most of these debris avalanches are subaerial (98.4%); no comparison is made between subaerial and submarine deposits because there are too few of the latter and results will not be representative.

The database is organized in five main sections which are also divided into several categories where fields are found (Fig.18). These sections have been listed from the general information (identification and general settings), to the information regarding the debris avalanche.

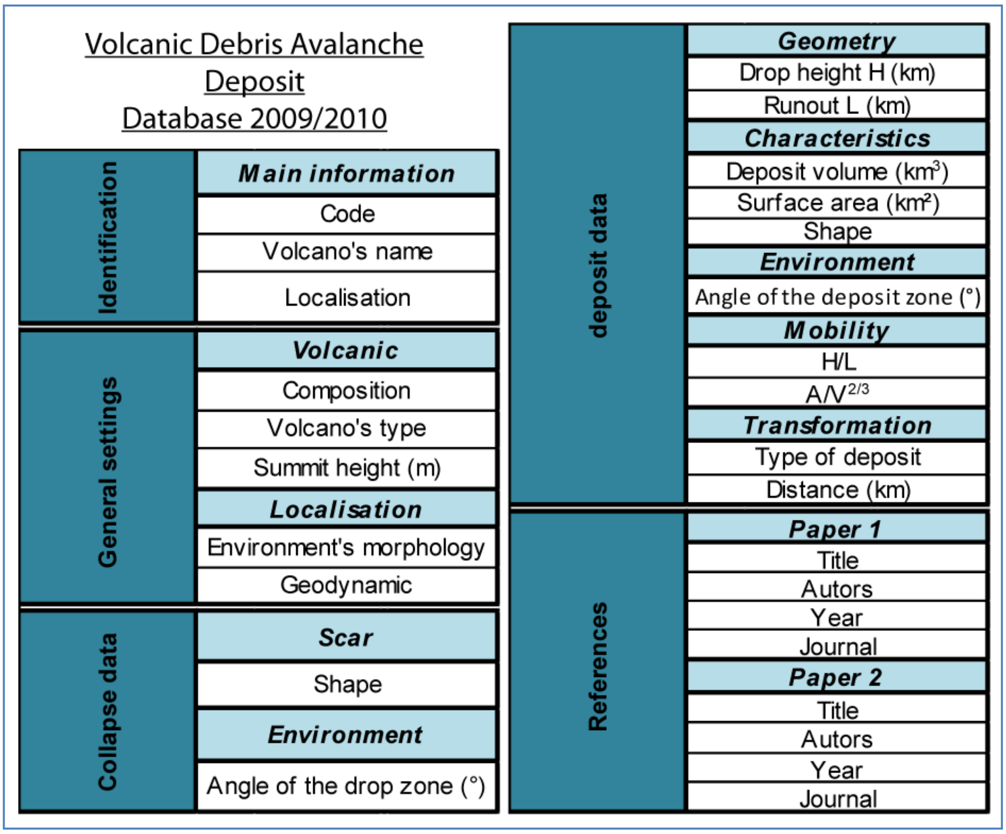


Figure 18. Parameters of the database of this study

II. Statistical analysis

The database has been used for two different kind of statistical analysis; first using *Microsoft Excel* in order to have a global view of the results and to compare it with pre-existing knowledge. The other statistical analysis used *XLSTAT* software to study correlations between parameters.

II.1. Analysis with two variables

Since the beginning of studies on debris avalanches, scientists have tried to correlate different parameters. As their databases were small, the present aim is to supplement their analyses. In the literature, four main parameters have been used: volume (V), surface area (S), vertical height of drop (H) and horizontal runout (L).

II.1.1. Methodology

In order to compare the results with earlier studies (Ui, 1983; Ui et al, 1985; Hayashi & Self, 1992) data have been presented graphically. However as the present goal is to study the effect of the topography on debris avalanche deposits, volumes have been categorised as small, medium and large (Tab.3, with DA: Debris Avalanche).

	Small DA	***Medium DA***	***Large DA***
Volume (km^3)	] 0.1 ; 1]	] 1 ; 10]	] 10 ; 100]

Table 3. Classification of debris avalanche volume

For the database, four different data sets were used. The first comprises 119 deposits where three parameters are known (H, L and V). As some data were missing for the fourth parameter (S), the second set contains 90 deposits. However some data seemed false (Iliamni) and as pointed out by Davies and McSaveney (1999), with volumes less than $0.1km^3$ the behaviour is fundamentally different, so a third set of 80 data was created to avoid these data. It is important to have comparable numbers of debris avalanches in all categories to avoid biasing the results. Note that Ui's database differs from that of Hayashi and Self in having no large debris avalanches (Tab.4).

	Volume (km^3)		
References	***Small DA***	***Medium DA***	***Large DA***
Ui, 1983	9	8	0
Hayashi & Self, 1992	21	14	6
Data set n°1	55	45	19
Data set n°2	36	35	19
Data set n°3	31	34	15
Data set n°4	31	34	0

Table 4. Volume partition in the classification for each study

One of the hypotheses of this study is that the volume of debris avalanche influences the impact of environment morphology on the deposit. Thus a fourth data set was created with only small and medium debris avalanche data; it was also a way to have an equivalent amount of debris avalanches of different volume. If the hypothesis is correct, then small and medium debris avalanche data will plot differently from data of all sizes.

II.1.2. Correlations

The coefficient of correlation (R^2) gives an idea of the degree of scatter of data (Tab.5).

	Parameters					
Reference	***H vs L***	***L vs V***	***S vs V***	***H/L vs V***	***H/L vs S***	***H/L vs S/V$^{2/3}$***
Ui, 1983	0,677	0,659	-	0,246	-	-
Hayashi & Self, 1992	0,831	0,709	-	0,304	-	-
Data set n°1	0,564	0,321	-	0,183	-	-
Data set n°2	0,575	0,372	0,461	0,223	0,570	0,419
Data set n°3	0,653	***0,504***	0,642	0,328	0,426	***0,180***
Data set n°4	0,595	***0,424***	0,609	0,370	0,394	***0,185***

Table 5. Coefficient of correlation R^2 from different data sets

The closer R^2 is to 1, the better correlated are the data. Results from the database created for this study are quite different from those found by Ui (1983) and Hayashi and Self (1992), especially for the two first comparisons (***H vs L and L vs V***). The difference is also present between those Ui and Hayashi and Self, however it is less important. Several reasons can explain these differences:

1. the difference of number of debris avalanches used is different
2. the number of different volume debris avalanches is not the same,
3. Ui's database included no large debris avalanches.

To delete too many data might also influence the results, however the R^2 values for *H/L vs S/V$^{2/3}$* of data sets 3 and 4 are very similar to each other which is not the case with data set 2. So the variation observed between data sets 3 and 4 is not due to the fact that there are less data.

Regarding parameters H, L and S, the difference between large and other debris avalanches is not very important. These parameters are thus not the best to explain any difference between different volumes of debris avalanches. However, they are better correlated (40% on average) than are V, L and H (34% on average).

The most notable difference in R^2 values (8%) between data sets 3 and 4 is that for *L vs V*. L and V are much better correlated if large debris avalanches are present, even if the correlation is not very good because in the best case less than 50% of the data are explained. This observation applies between H and L or S and V as well, which means than at least one common parameter is responsible for these results. So statistical analysis seems to indicate that environment has an impact on debris avalanche deposits, and this is sensitive to the volume of the debris avalanche. The bigger the avalanche, the less the effect of the topography. However, medium debris avalanches are better correlated than small debris avalanches (R^2 = 0.126 vs R^2 = 0.061). This might be due to the fact that small debris avalanches can be affected by a topography that is very variable at a small dimension.

II.1.3. General distribution

Trying to find a general tendency between data is interesting, however if the correlation is not sufficient (less than 75%), it is better to deal with the areal distribution of the data (Fig.19).

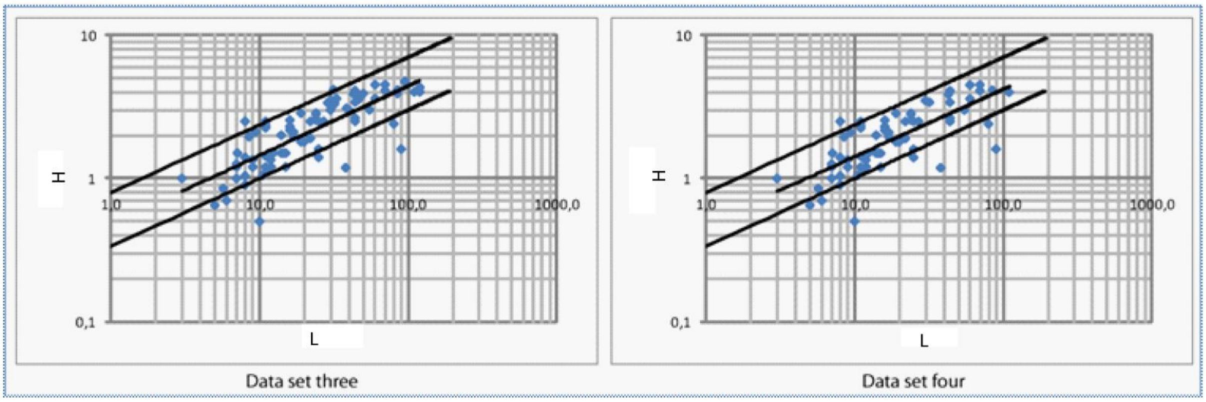


Figure 19. Distribution of the data for data sets 3 and 4

It is interesting to see that most of the data lie between two parallel lines ($y = 0.7997x^{0.4711}$and $y = 0.3333x^{0.4771}$), both with and without large debris avalanches. So the general tendency for the data is not a line but a narrow field. As some debris avalanches from dataset 3 are known to have transformed into debris flow (or lahar), they have been plotted in a different color and form (Fig. 20).

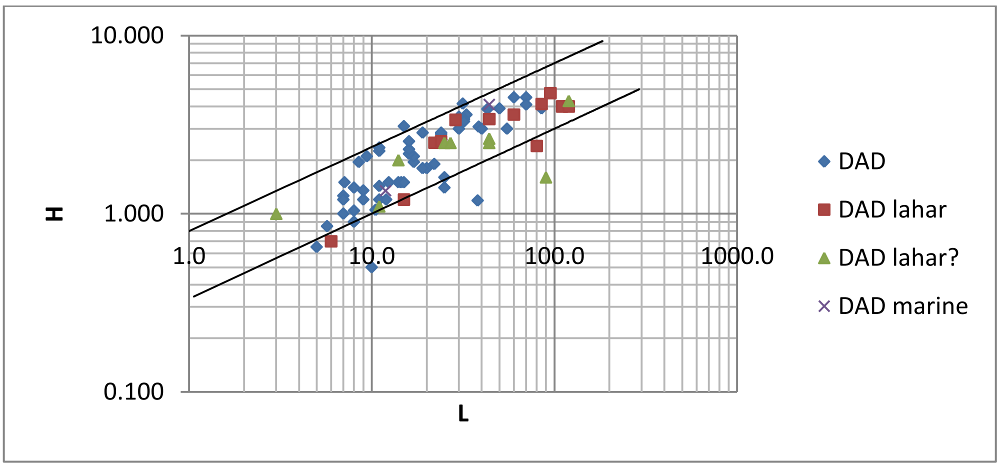


Figure 20. Distribution of debris avalanches differentiating those which transformed into lahars

No general tendency seems to exist for debris avalanches that transformed into lahars. However when volume is also considered still using dataset 3 (Fig.21) it is evident that small debris avalanches usually have low values of H and L whereas large debris avalanches are characterized by high values for H and L. Medium debris avalanches are more scattered on this graph.

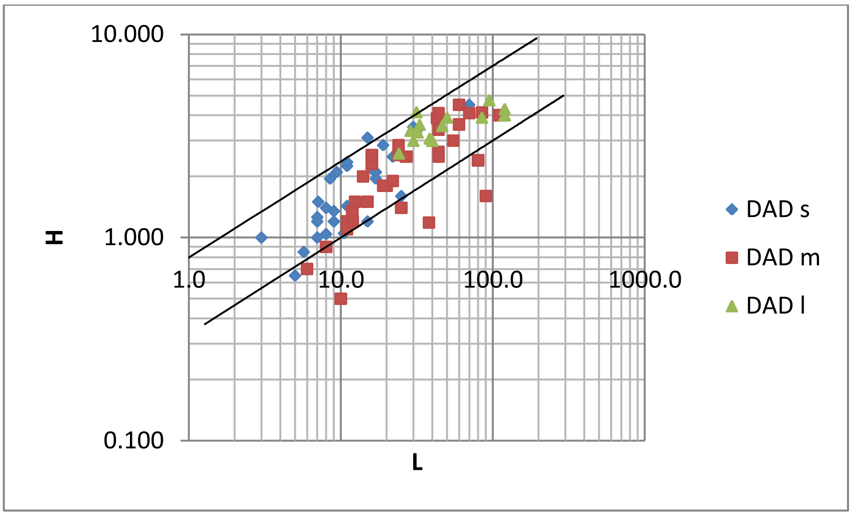


Figure 21. Graphic of distribution of debris avalanches considering their volume

As the result, even if some events do not follow a general tendency, it seems that volume is somehow linked with H and L: the larger the volume, the larger H and L. The second observation is that medium debris avalanches tend to have H and L closer to large ones than to small ones.

II.1.4. Slope angles of the drop zone and the deposit zone

This study is the first to consider the average slope angles of the drop zone and the deposit zone. Graphs have been plotted to see if any general tendency exists (Fig.22 & Fig.23).

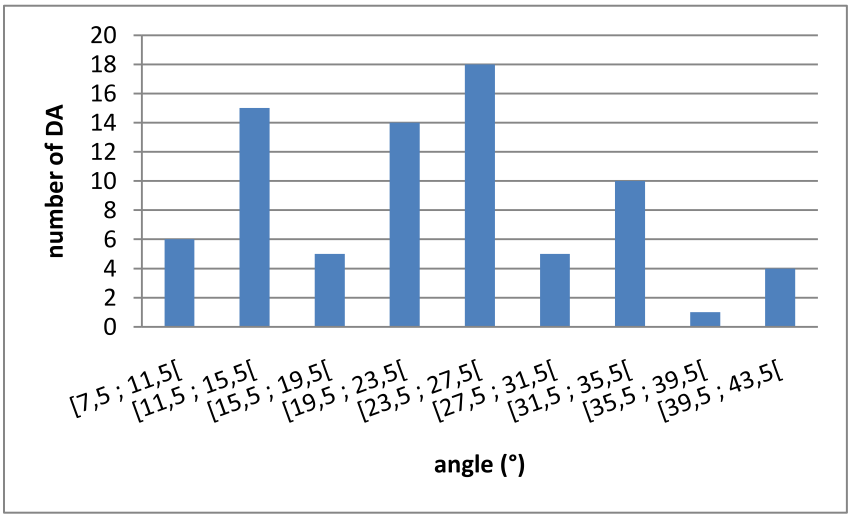


Figure 22. Distribution of debris avalanche drop zone slope angles

The drop zone slope data are quite scattered. Even if 51% of the data are represented by the four first categories, the angle of a drop zone seems to be in general (41%) between 19° and 32°. However, the data are not sufficient enough to define a general tendency.

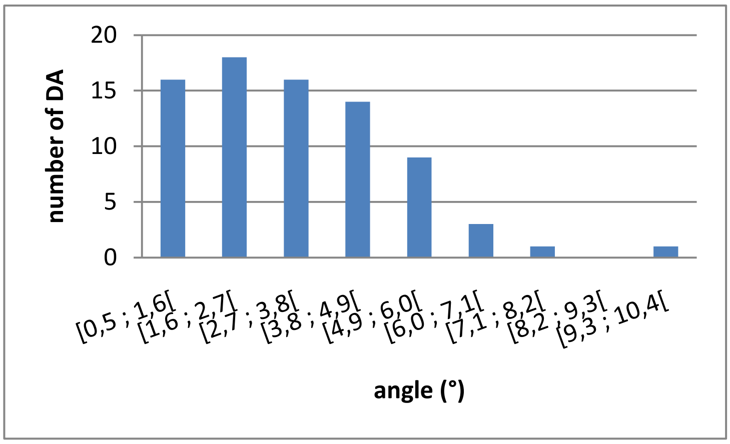


Figure 23. Distribution of debris avalanche deposit zone slopes

Not surprisingly the larger the slope, the fewer the deposits. This is illustrated by the fact that the three first categories of deposit slope angle represent 64% of debris avalanche deposits and just by addition of the fourth category 82% of the data are represented. In conclusion most deposits appear on relatively flat area (slope < 5°). In addition, there is no apparent relation between drop zone slope and deposit slope (Fig.24).

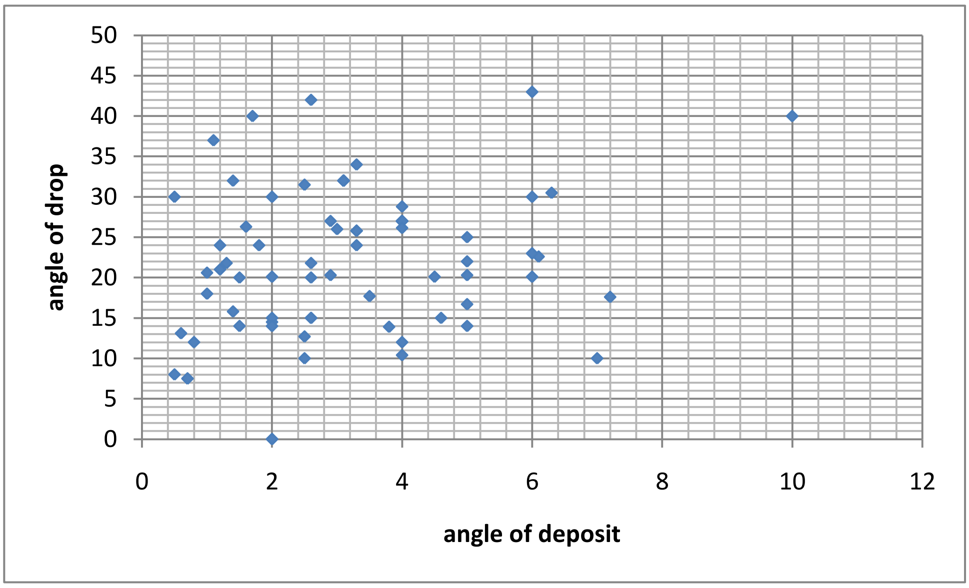


Figure 24. Angle of deposit vs angle of drop

As the numbers of debris avalanche deposits are linked with the slope angle of the deposit zone, it seems interesting to see the relation between H/L ratio known as the mobility and the slope angle of the deposit zone.

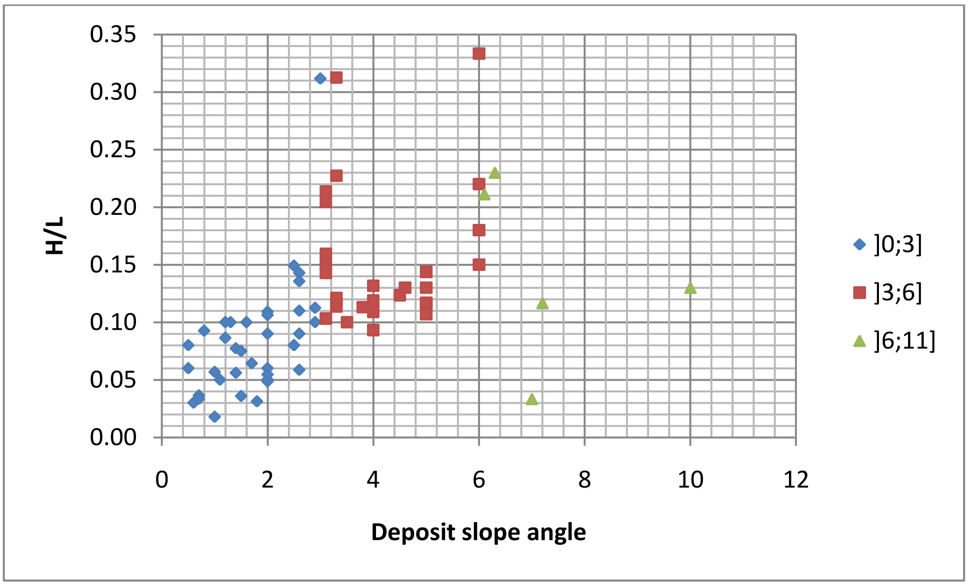


Figure 25. Deposit slope angle vs H/L

It is quite obvious to notice that H/L ratio and the deposit slope angle are negatively linked together, the smaller H/L, the lower the deposit slope angle (Fig.25). To put it a different way, the bigger the mobility the lower the deposit slope angle. The next interesting parameters to analyse together is the deposit slope angle with the runout (Fig.26).

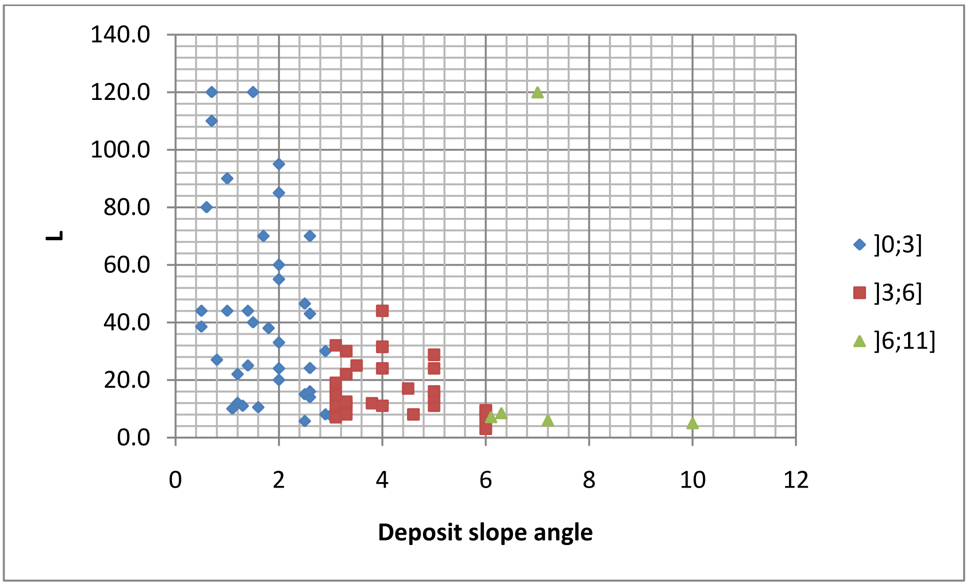


Figure 26. Deposit slope angle vs the runout

As a result the bigger the runout the lower the deposit slope angle. It is logical if it is supposed that slope angle of a volcano tend to be lower with the increase of the distance from the summit of the volcano.

Analysis of two variables is a good way to derive some hypotheses and to test preliminary ideas such as the fact that the bigger the mobility, the bigger the runout and the lower the deposit slope angle. However, it is also interesting to do multivariate analysis.

II.1.5. Relation between the morphology of the environment and the shape of the deposit

It seems logical that if the morphology of the environment has an impact on debris avalanches then the shape of the deposit should reflect it. To verify this, the number of events of each kind of main morphology of environment has been counted for each shape of deposit (Tab.6; e.g. Chapter 1 - III.1.2)

	Morphology of the environment					
	Number			Percentage		
Shape	**Unconfined**	**Confined**	**Semi-confined**	**Unconfined**	**Confined**	**Semi-confined**
Fan-shaped	15	2	1	83	11	6
Digitate	2	1	0	67	33	0
Round	1	0	0	100	0	0
Elongate	3	11	7	14	52	33
Winding	0	16	0	0	100	0
Lobate	5	2	1	63	25	13

Table 6. Repartition of the data with respect to the shape of the deposit and the morphology of the environment

It is not surprising to see that all winding deposits and half of the elongate ones are associated with confined environments. Lobate, fan-shaped and digitate deposit shapes are mainly associated with unconfined environments. However a small percentage of deposits in confined environments might be the result of different properties of the debris avalanche (volume, water content ...). It is impossible to conclude anything regarding round deposits due to the small number of events with this shape (only one: the debris avalanche of Acatenango).

Debris avalanche deposits will preferentially have an elongate or winding shape in confined environments, whereas the shape will tend to be lobate, fan-shaped or digitate when unconfined. However deposit shapes for semi-confined environments are between those of unconfined and confined environments. It is possible that the properties of the debris avalanche (volume, water content...) may also affect the deposit shape.

As a result the classification of the deposit shape proposed by Bernand (2008) can be organised in two main categories (Fig.27). Shapes associated with an unconfined environment (fan-shaped, round and digitate) and those related with a confined environment (elongate, winding and lobate).

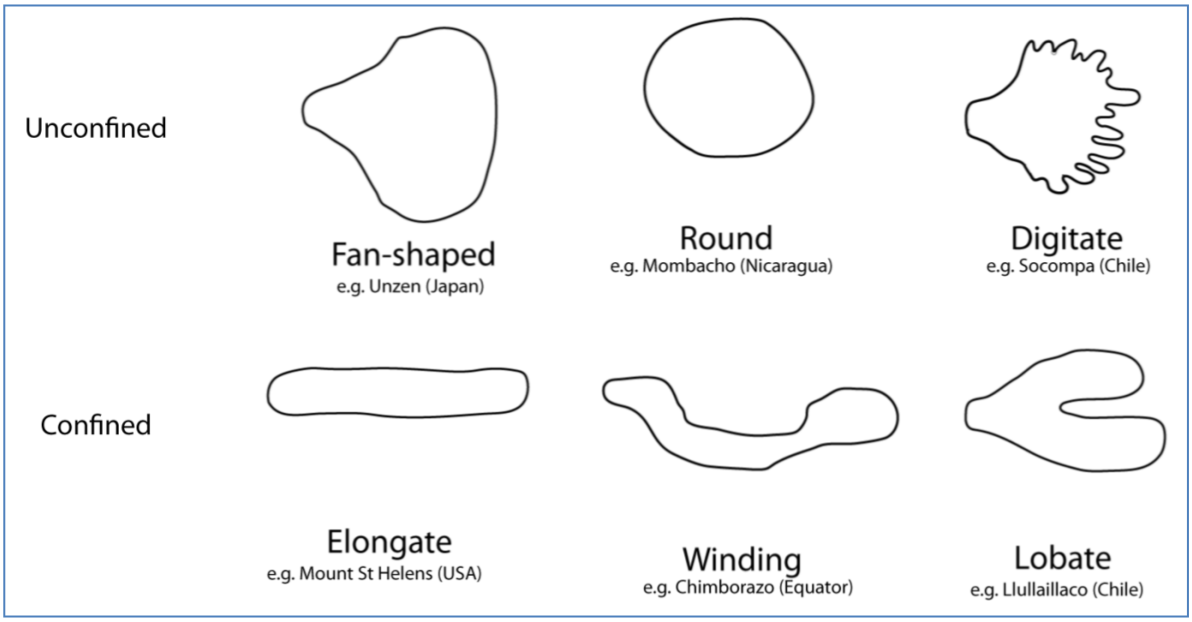


Figure 27. Deposit shape classified regarding the environment

II.1.6. Relation between the morphology of the environment and the runout

Another interesting aspect was to see if the morphology of the environment has an impact on the runout of debris avalanches. To illustrate this, Fig.28 shows runout plotted against H with morphology of the environment as a parameter using deposit from dataset 3 with information regarding the morphology of the environment.

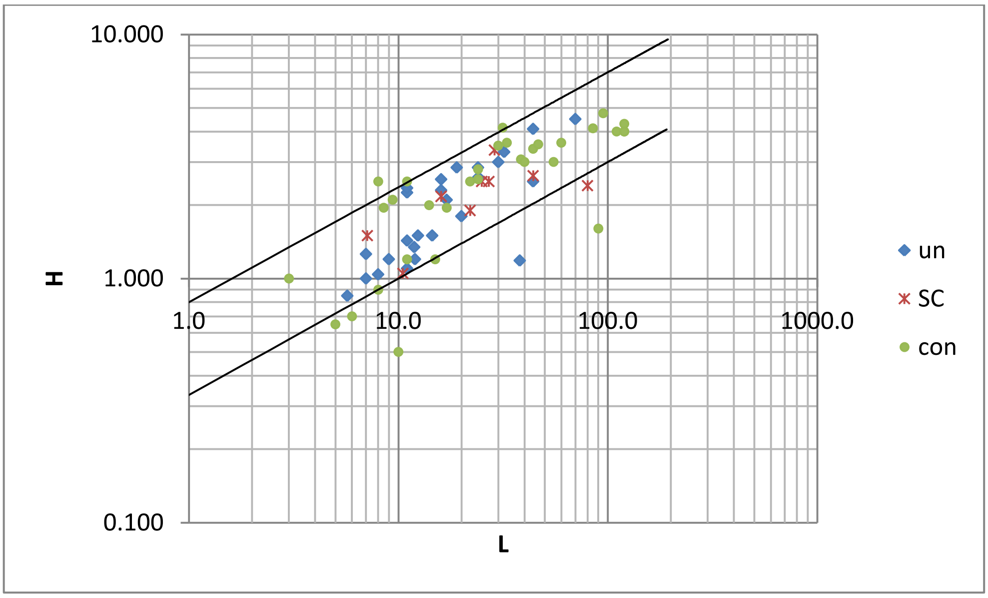


Figure 28. Plot of L vs H for debris avalanches as influenced by the morphology of environment (un: unconfined, sc: semi-confined, con: confined)

Even if there is no strict separation between data with different morphologies, there seems to be a general tendency. Most of the unconfined data plot at the lower values for the runout and the height whereas confined debris avalanches seem to plot at higher values. Semi-confined data are scattered in between but are less represented as there are less cases present in the database. However these results might due to a bad proportion of values from data and the effect of the volume. To see this, average of volume and runout for each category have been calculated (Tab.7). It is important to notice that the more data, the closer to the category average the parameter average will be, and that some categories are poor in data (for example semi-confined debris avalanches).

		Volume		
		[0,1 ; 1,0]	]1,0 ; 10]	]10 ; 100]
Number				
Environment	Unconfined	12	11	3
	Semi-confined	4	4	1
	Confined	8	13	9
Average of V				
Environment	Unconfined	0,5	3,1	20
	Semi-confined	0,8	5,8	14
	Confined	0,4	3	28,7
Average of L				
Environment	Unconfined	15,9	22,7	28,7
	Semi-confined	14,2	43,3	28,8
	Confined	13,7	41,6	71,6

Table 7. Average of L and V factors for each category of debris avalanches

Due to the small number of large debris avalanches, their results are not interpreted. Except for semi-confined debris avalanches, the average for the volume is almost the same for small, medium, unconfined and confined debris avalanches. The difference between unconfined and confined debris avalanches is slightly bigger for large ones, but it might be the result of data error margin. As a result, the runout is almost identical for small unconfined and confined data whereas for medium debris avalanches the confined runout is almost the twice that of unconfined ones.

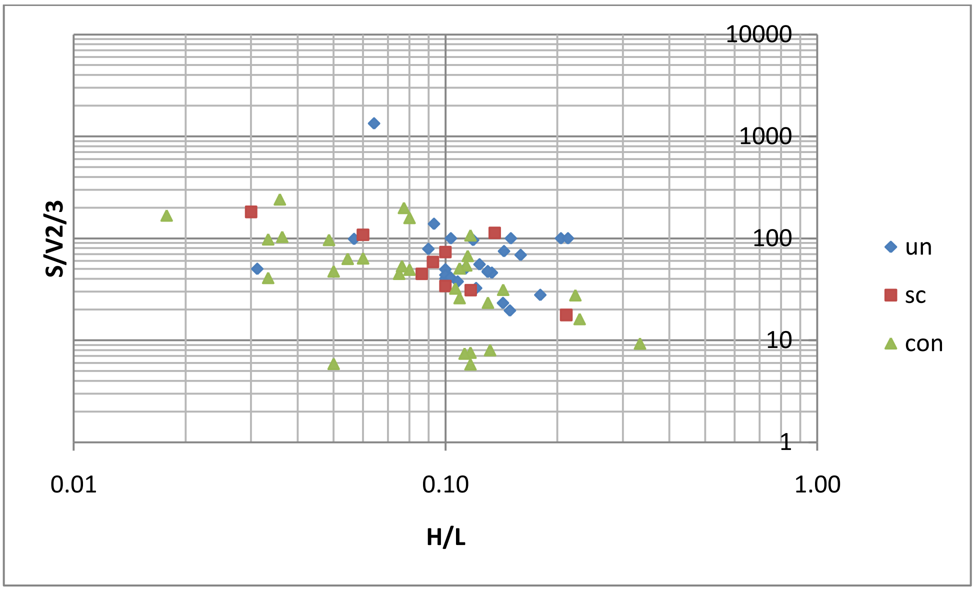


Figure 29. H/L vs S/V2/3 (un: unconfined, sc: semi-confined; con: confined)

Looking at the relation between H/L ratio (the mobility) and $S/V^{2/3}$ ratio (which can be associated to a spreading factor), it is pointed out that for an equal $S/V^{2/3}$ confined debris avalanches tend to have a lower H/L ratio (Fig.29). This means that confinement has an impact on the mobility and the spreading of the avalanche.

These results contrast with those found of Shea and Van Wyk de Vries (2008) using analogue modelling experiments; they showed that the confinement had no impact on the runout but only on the shape and thickness of the deposit. However the same analyses should be done with a bigger dataset as some categories are quite low in cases (for example there is only one case for a semi-confined large debris avalanche).

II.2. Analysis with multiple variables

Two-dimensional analyses are useful because they provide preliminary information and ideas. However, sometimes it is also interesting to compare several parameters at the same time. First the software used will be introduced, before the analysis and the results are described.

II.2.1. XLSTAT2009 software

Several software packages exist for multiple dimension analysis such as *Statbox*, *Statistica*, *XLSTAT* and *R*. The main differences are the price, the ease of use and also of manipulation of the data.

II.2.1.1. Presentation and aim

XLSTAT software was created in 1993 by Addinsoft. The main advantage is its simplicity of use because the interface is under *Microsoft EXCEL*, which allows easy data input and modification if needed. However all calculations are done by independent programs. Different ways to study data are possible such as preparation, description, analysis, visualisation and modelling, also some statistical tests and a tool box.

II.2.1.2. Prerequisites

Analysis cannot be completed without paying attention to some important criteria. This will be explained by using as an example the statistical analysis that needs to be done following water analysis. The main criterion is the organisation of the data, which are entered into an *EXCEL* table. In this table, columns represent quantitative ***variables*** such as chemical elements in our example, and lines stand for ***samples***, for example the location of sampling. If the first column is used for the name of each sample, the identification process will be easier. Another important criterion is that every single field has to be filled in, that is why data must be carefully selected.

At the end, the *EXCEL* table which summarizes all data is called a ***matrix***. So if the chemical properties of the water of Auckland in New Zealand needed to be analysed, the matrix could be constructed from average weekly tests of 1995 and would comprise 10 samples and 10 variables (Fig.30).

Identification	pH	Cl (mg.L^{-1})	F (mg.L^{-1})	SO_4^{-2} (mg.L^{-1})	$CaCO_3$ (mg.L^{-1})	Al (mg.L^{-1})	Fe (mg.L^{-1})	Mn (mg.L^{-1})	Na (mg.L^{-1})	K (mg.L^{-1})
Andomore 1	7,0	11,6	0,04	2,2	13,9	0,15	0,34	0,03	8,4	1,16
Andomore 2	7,8	12,6	0,86	8,4	17,0	0,02	0,01	0,01	9,0	1,11
Papakura 1	6,9	15,5	0,04	3,3	13,0	0,46	1,72	0,07	10,5	1,89
Papakura 2	7,9	17,3	0,03	19,0	16,8	0,02	0,01	0,01	11,4	1,86
Huia 1	7,0	20,0	0,02	3,1	14,7	0,31	0,58	0,03	12,4	0,89
Huia 2	7,8	21,6	0,85	13,1	15,7	0,02	0,01	0,01	13,4	0,89
Waitakere 1	6,9	22,2	0,01	3,1	14,1	0,28	0,63	0,01	13,4	0,97
Waitakere 2	7,7	23,0	0,83	13,0	14,3	0,02	0,01	0,01	13,5	0,98
Onehunga 1	7,3	18,0	0,16	14,7	57,3	0,01	0,01	0,01	19,8	3,39
Onehunga 2	7,7	20,0	0,15	15,2	58,2	0,03	0,01	0,01	22,5	3,29

Figure 30. Example of matrix from the results of water analysis in Auckland (data from the NZIC: New Zealand Institute of Chemistry)

II.2.1.3. Statistical analysis tools

Two main categories of method are recognised for analysis with multiple variables: the descriptive method and the explicative method.

The aim of the descriptive method is to organise and simplify data from several variables without focusing on any variable in particular. Several analyses can be done but the four most usual are (depending on the aim of the analysis and the type of data available):

- Principal Components Analysis (PCA)
- Factorial Analysis of Correspondence (FAC)
- Multiple Correspondence Analysis (MCA)
- Topology and Methods of Classification

The aim of the explicative method is to explain one variable by using two or more other variables. There are three main tools:

- Multiple Regression
- Distinguishing Method
- Segmentation

For this study, one tool from each method will be used; PCA for the descriptive method and Multiple Regression for the explicative method.

II.2.2. Principal Components Analysis

Before presenting the results of the analysis with multiple variables on the database, the principles of PCA will be introduced and the methodology used for this study will be explained.

II.2.2.1. Principles

A PCA (Principal Components Analysis) is a descriptive method that summarizes information from the ***matrix***. This method was invented by Pearson (1901) and Hotteling (1933) but has been widely used only for the few last years. It is a useful statistical technique which uses mathematical concepts (deviation, covariance, eigenvectors and eigenvalues). The aim of this method is to highlight similarities and differences of the data graphically. As a result, correlations between data patterns are represented by the creation of two new perpendicular axes which reduce the number of dimensions without much loss of information.

PCA results are presented as variables plots, observations plots and the contribution of the variables. Each gives different information; we illustrate this with the same example as before (water analysis of Auckland). The observations graph is used to determined data groups to know which data tend to behave in the same way, and also to identify data that have a completely different behaviour (Fig.31).

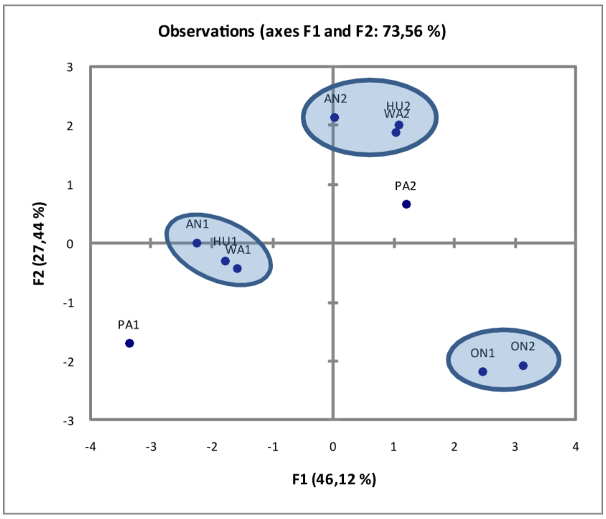


Figure 31. Observations plot for the Auckland water analysis

For example, in this graph it is clear that three main groups exist and that data from Papakura are very different from other data. The two samples from Onehunga act the same way and comprise one group, whereas other localities have the same behaviour. As it is important to find out the significance of each axis (F1, F2 ...), analysing the contribution of variables might be useful (Tab.8).

	F1	F2	F3
pH	13,763	11,419	4,626
Cl	3,004	0,064	***67,301***
F	2,627	***23,955***	0,112
SO_4^{-2}	***19,402***	0,429	1,427
$CaCO_3$	12,603	16,500	0,781
Al	***17,682***	6,134	3,954
Fe	9,474	5,335	7,600
Na	13,328	13,095	7,461
K	8,117	***23,069***	6,737

Table 8. Example of contribution of variables from the Auckland water analysis

For instance, it is easy to see that the third axis is mainly the result of a property due to chloride anion. In addition, some links and influences between elements can be observed. In this case, SO_4^{-2} and Al are linked under axis 1 but not under axis 2. These relations between variables can be identified by using a variables plot graph (Fig.32).

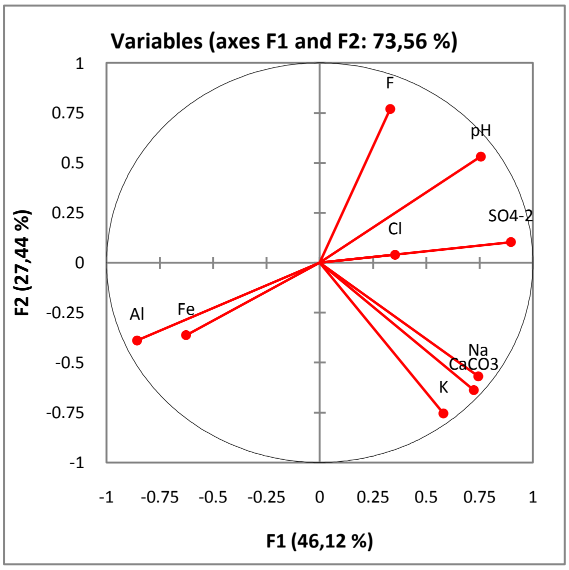


Figure 32. Graph of the variables plot for Auckland water analysis

To understand this, the first point is to identify variables which are well represented: the closer to the circle, the better correlated the data. Here Fe and Cl are poorly correlated whereas other data are good enough to be interpreted. The relative positions of the plots one to another have a meaning. The closer are two plots, the more similar the plots; so in our example $CaCO_3$ and Na have the same correlation. Two independent variables are represented by perpendicular vectors such as Al and K, whereas two variables with an opposite variation have an angle of 180° formed by their vectors (Al and pH for example). It is also interesting to look at the relation between these two plots, for this a biplot graph is used.

These relations highlighted through positive, neutral or negative correlations/links can have different signification. A link can be due to a mathematical relation for example if A/B ratio and A are positively correlated it is because if A increases, A/B ratio increases as well. However a link is unique to each case and is not a cause to effect relation. Each link needs to be studied in order to understand the element at the origin of the relation between the two variables.

Now that principles of PCA and the way to interpret it have been explained, the methodology used for this study will be introduced.

II.2.2.2. Methodology

The first step needed to carry out a PCA is to determine the parameters and data that will be used. For this study the six main parameters from the database (H, L, V, S, H/L & $S/V^{2/3}$) plus the two slope angles will be used. Then even if the morphology of environment is not a parameter it will be used to develop several data sets. In order to see the impact of every characteristic, some subdivision has been carried out and parameters have been added step by step. That is why several matrices have been used (Tab.9), and for each of them the first column is used as the identification column (ID).

Data set #	Characteristic	Subdivision	H, L, V, S, H/L & $S/V^{2/3}$	Addition of α_1 & α_2
Data set 1	All	-	80	73
Data set 2	Small	-	28	28
Data set 3	Medium	-	32	32
Data set 4	Large	-	13	13
Data set 5	Unconfined	All	26	26
		Small	12	12
		Medium	11	11
		Large	-	-
Data set 6	Semi-confined	All	9	9
Data set 7	Confined	All	30	30
		Small	8	8
		Medium	13	13
		Large	9	9

Table 9. Number of debris avalanches in every data set considering characteristics and parameters used

II.2.2.3. Analysis

To allow a better understanding of the results, three main kinds of analysis have been done.

II.2.2.3.1. General analysis

This first kind of analysis has been done on all the data to have a general view of any correlation.

II.2.2.3.1.1. With six main parameters

In order to understand the impact of each parameter on debris avalanche deposits, first the six known parameters (H, L, V, S, H/L and $S/V^{2/3}$) have been studied and slowly put together. The first analysis has been carried out with three parameters: H, L and V (Tab.10).

Parameter\Axis	F1	F2	F3
H	34.727	22.272	**43.002**
L	36.538	7.896	**55.566**
V	28.735	**69.832**	1.432

Table 10. Parameter contributions for H, L and V

The F1 axis of the parameters' contribution has about the same proportion of the different variables (33% each) which makes it difficult to analyse. However the F2 axis is dominated by the volume and the F3 axis by the height and runout. As a result the correlation between H and L is quite strong (F3: H=43% and L=56% whereas V=1%).

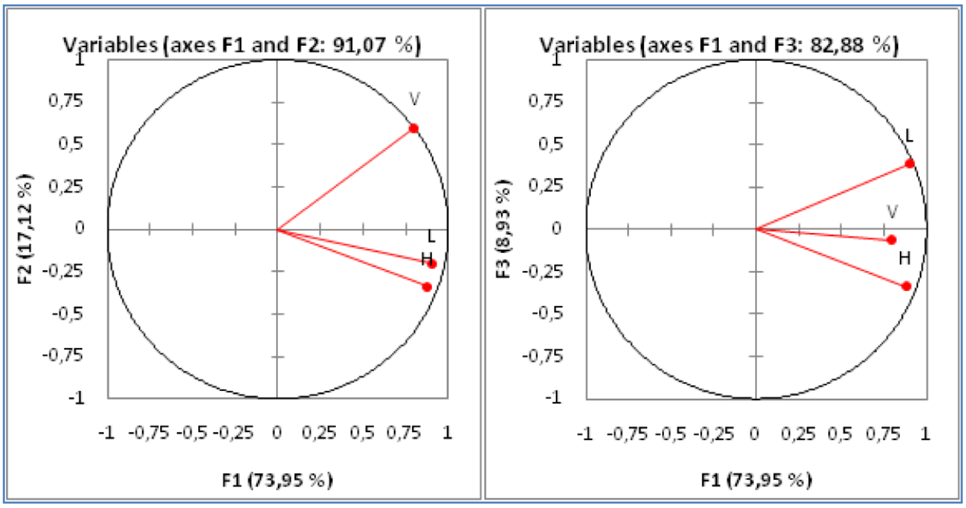


Figure 33. Representation of the variables (H, L and V)

The variables are very well represented under the F1-F2 axis (Fig.33). As expected H and L are strongly positively correlated and both are almost independent of V (small positive correlation). Under the F1-F3 axis, variables are well represented even if V is not as well represented as before. L and H are still positively correlated but less strongly than before. V appears to be between L and H, which gives a positive correlation with these variables. However all variables are quite near to the F1 axis which is characterized by no clear distinctions between variables.

The same analysis was carried out with the addition of the surface area (S) to see its impact on the correlation between the variables (Tab.11).

Parameter\Axis	F1	F2	F3	F4
H	24,992	29,824	13,871	31,313
L	**27,552**	10,482	0,001	**61,964**
V	21,96	**56,457**	21,58	0,003
S	**25,496**	3,237	**64,547**	6,72

Table 11. Parameter contributions for H, L, V and S

This addition decreases the correlation between V and the two other variables H and L under the F1 axis. The F2 axis is dominated by the volume whereas the F3 axis is dominated by S. The last axis (F4) is dominated by L; it seems that H and L are well correlated whereas V and S are less well correlated and not very strongly correlated with H and L.

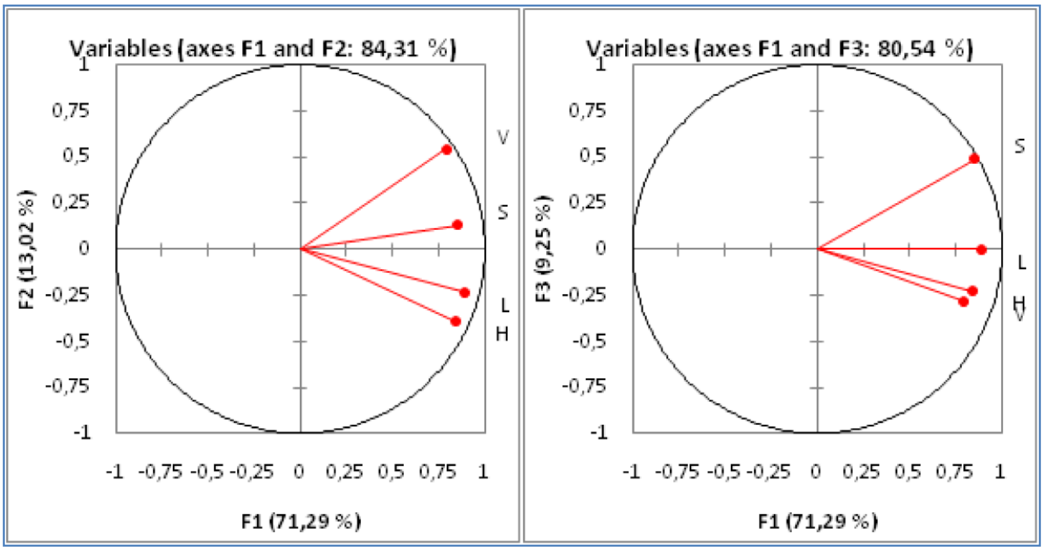


Figure 34. Representation of the variables (H, L, V and S)

Addition of S reduces somewhat the representation of data (Fig.34). Relations between H, L and V are almost the same regarding the target representation under the F1-F2 axis. However, the correlation between H and L is a little less important than before. S is between L and V, so its correlation with V and with L is almost the same. Under the F1-F3 axis, variables H and V are a little further from the circle and are very positively correlated together.

Parameter\Axis	F1	F2	F3
H	19,41	0,217	**15,544**
L	24,332	0,262	2,443
V	15,032	**29,668**	5,173
S	21,042	0,044	5,048
H/L	13,635	0,041	**70,969**
$S/V^{2/3}$	6,548	**69,767**	0,823

Table 12. Parameter contributions for the six parameters

It is rather difficult to analyse the F1 axis as most variables are similar, however other axes seem to have strong characteristics (Tab.12). The F2 axis is dominated by $S/V^{2/3}$, however it is quite clear that the correlation with V is much stronger than that with S. Looking at the F3 axis, the dominant variable is H/L; the correlation for this variable is more important with H and L. One interesting aspect of the F3 axis is the strong correlation between V and S.

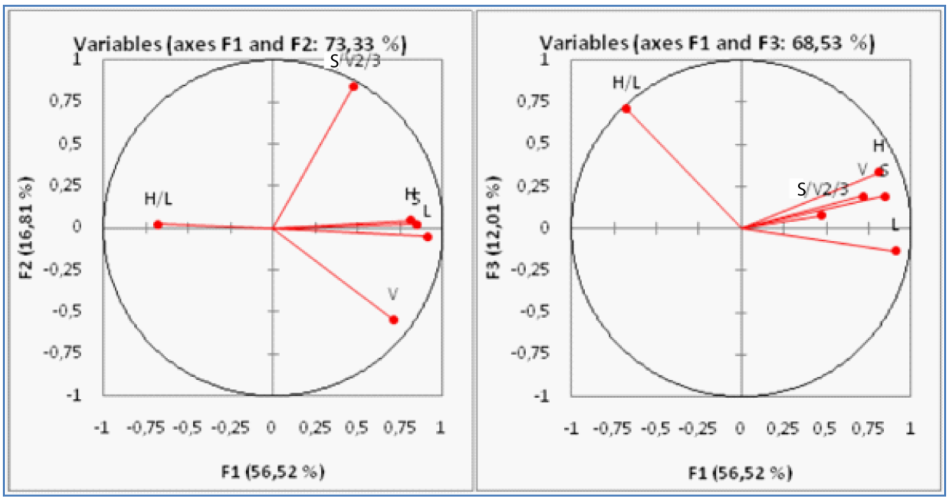


Figure 35. Variables representation (L, H, V, S, H/L and S/V2/3)

The first observation is that the greater the number of variables, the more information is lost (Fig.35). However regarding the F1 axis, variables are well represented with H/L as an exception. $S/V^{2/3}$ and V are independent in this representation which seems quite strange, whereas H, S and L are very well correlated. Under the F1 and F3 axis, $S/V^{2/3}$ and V are badly represented, whereas H/L and L are anticorrelated which is logical. However H/L is almost independent of H, which is quite strange, and S is better correlated with H and L.

II.2.2.3.1.2. Addition of the angle of the drop and deposit zones

The next step was to add the two slope angles to see their impacts (Fig.36). First we see if there are any correlations between the two angles. In fact, the two angles are independent which seems logical.

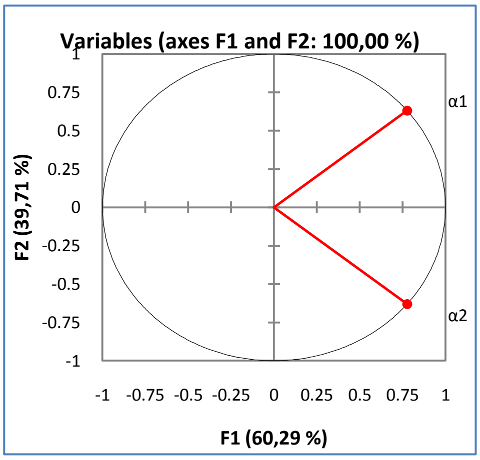


Figure 36. Representation of variables α1 and α2

Then the runout was added:

	F1	F2	F3
L	**40,928**	0,117	**58,955**
α_1	30,596	**45,304**	24,100
α_2	28,476	**54,579**	16,945

Table 13. Variable contribution for α1, α2 and L

On the F1 axis it seems that L is the dominant variable however the two other parameters are only a little less influential (Tab.13). The F2 axis is clearly dominated by the two angles, whereas the F3 axis is mainly affected by L.

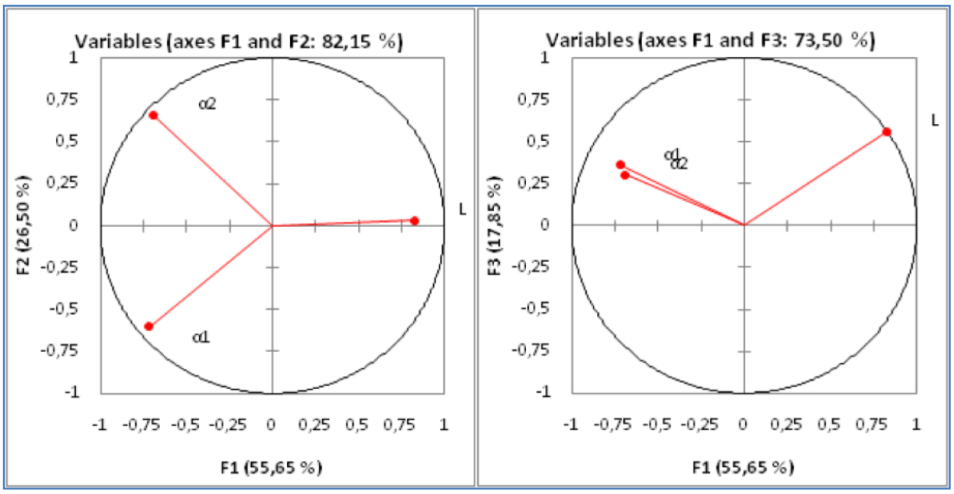


Figure 37. Representation of variables α_1, α_2 and L

Under the F1-F2 axis, it is quite obvious that α_1 and α_2 are independent (Fig.37). Variable L is not very well represented under F1-F2 but is very close to the F1 axis whereas α_1 and α_2 are almost in the middle between the F1 and F2 axes. L is better represented under F1-F3 however α_1 and α_2 are not well represented.

Parameter\Axis	F1	F2	F3
L	**37,363**	0,001	8,145
V	26,333	27,604	13,891
α_1	23,419	0,559	**75,609**
α_2	12,885	**71,837**	2,356

Table 14. Contribution of variables α_1, α_2, L and V

On the F1 axis, L is the most important parameter even though the values vary little (Tab.14). The F2 axis however is mainly affected by the angle of the deposit, whereas F3 is associated with the angle of drop.

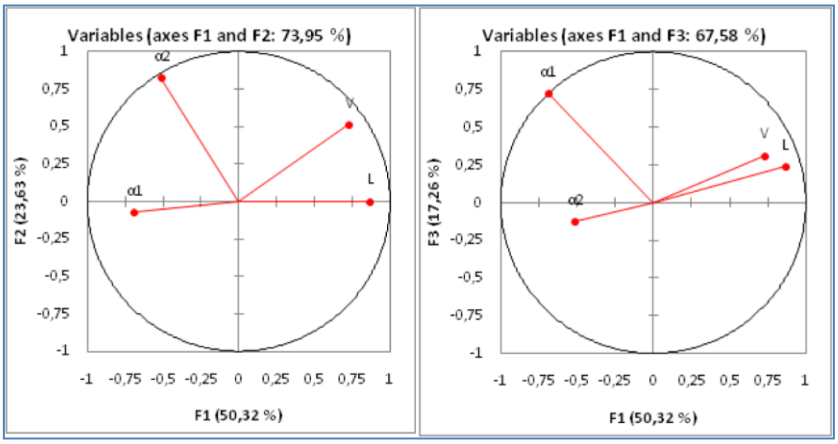


Figure 38. Variables representation of α1, α2, L and V

Under the F1-F2 axis, the angle of drop is poorly represented and is not analysed (Fig.38). The angle of deposit and the volume are independent, whereas the angle of deposit is correlated with the runout which is on the F1 axis. However under the F1-F2 axis, the angle of drop is almost independent of both variables V and L. Is it impossible to analyse both angles at the same time due to the poor representation of one of them each time.

The next step was to add the height:

Parameter\Axis	F1	F2	F3
H	26,529	1,071	14,959
L	**31,237**	0,034	1,972
V	20,739	24,302	0,125
α_1	13,047	0,217	**81,681**
α_2	8,448	**74,376**	1,264

Table 15. Variables contribution for α_1, α_2, H, L and V

The addition of H changes little (Tab.15).

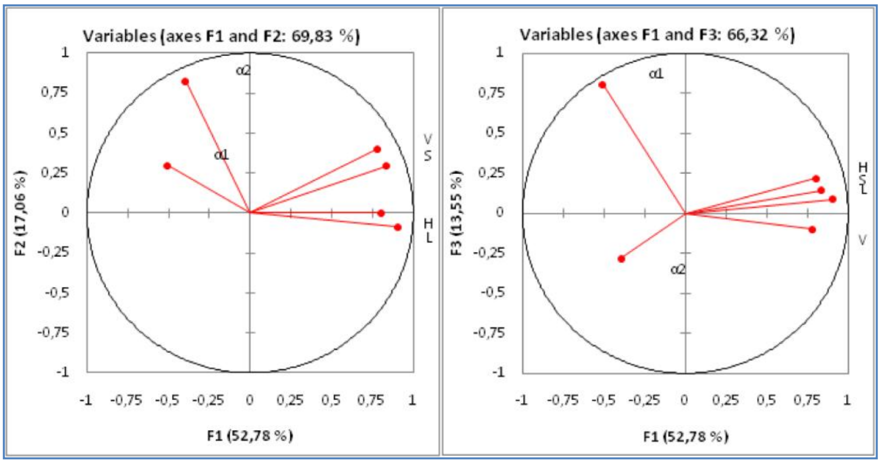


Figure 39. Representation of variables α_1, α_2, H, L and V

As before it is impossible to analyse both angle variables due to the poor representation of one of them each time (Fig.39). Under the F1-F2 axis, addition of H changes little; H and L are positively correlated together whereas H and the angle of drop are slightly correlated. However, under the F1-F3 axis it is interesting that the angle of drop is better correlated with the runout than H. Actually angle of drop and H are almost independent. The representation of the volume is not as good as before under these axes.

Addition of the area of deposit does not change the contribution of variables much. The main difference is that the relations between other variables and V are less important once S is added.

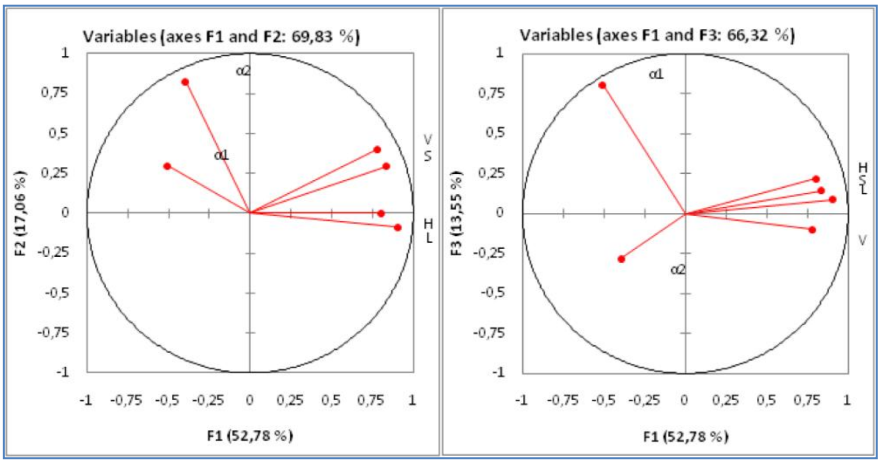


Figure 40. Representation of variables α_1, α_2, H, L, V and S

Under the F1-F2 axis, the angle of drop and H are poorly represented and will not be analysed (Fig.40). Regarding the same variables as those used for the previous PCA there are no major changes, however S is close to V under F1-F2 whereas it is farther from V but not very well represented under F1-F3.

The last step was to all the data together:

	F1	F2	F3
H	**16,440**	1,177	6,153
L	**22,482**	0,000	0,034
V	12,667	12,789	14,021
S	**17,391**	0,177	10,818
H/L	14,321	0,021	**19,293**
$S/V^{2/3}$	4,292	**51,679**	0,825
α1	5,687	**30,039**	7,662
α2	6,720	4,117	**41,193**

Table 16. Contribution of variables α_1, α_2, H, L, V, S, H/L and $S/V^{2/3}$

As before, H/L is better correlated with H than L (F3), whereas $S/V^{2/3}$ is better correlated with V than S (F4). The correlation between the angle of the deposit zone and H/L is shown by the F3 axis (Tab.16).

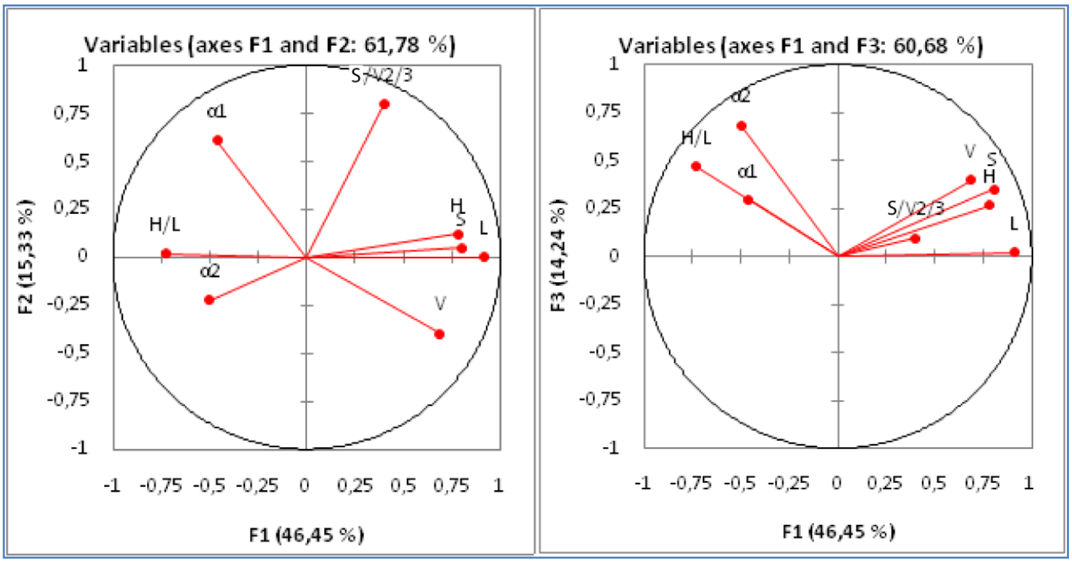


Figure 41. Representation of the variables α_1, α_2, H, L, V, S, H/L and $S/V^{2/3}$

The representation of variables is not very good; however a few relations can be seen (Fig.41). The best correlation is under the F1-F3 axis, with positive correlation between H/L and the angle of the deposit zone. Under the same axis it is possible to see that H/L and L are anticorrelated (which is logical) and L is still on the F1 axis.

II.2.2.3.1.3. Conclusion

All the results have been summarized in order to have a better understanding and global view of the correlations between these eight parameters (Tab.17).

Variables	Positive links	Negative links	Link with samples
H, L, V	L, H	-	H, V
H, L, V, S	L, H, S	-	H, V
H, L, V, S, H/L, $S/V^{2/3}$	L, H, S	H/L, L	H/L, V
L, V, α_1, α_2	L, V	-	α_2, L or V
L, H, V, α_1, α_2	L, H	-	α_2, H or L or V
H, L, V, S, α_1, α_2	H, L ; S, V	-	α_2, H or L or V
H, L, V, S, H/L, $S/V^{2/3}$, α_1, α_2	L, S, H; H/L, α_2	H/L, L	H/L, α_2 or V

Table 17. Results of the correlation of the eight parameters for all data used

The results of the general PCA is that, irrespective the number of variables used, if the height increases then the runout increases.

Another result is that, as soon as the deposit surface parameter is introduced, then the positive correlation of the volume with the runout and the height decreases. In other words, when the surface of the deposit is considered, then if the height and the runout increase the volume increases, but not as much as it was increasing when the deposit surface was not used.

An interesting observation is the positive correlation between parameter H/L and the angle of the deposit zone. It appears that the more important the factor H/L, the longer the deposit - even though the angle of the deposit zone is not directly correlated with the runout or the height.

Regarding the distribution of the samples, most of them are represented by factor H/L. If this factor is not used then samples will be represented by parameter H, however H/L is preferable to H. The second vector direction used by samples is the volume, however if the angle of the deposit is used then this becomes the second vector direction of the samples. In other words, the second parameter which represents most of the sample is the volume if the angle of the deposit zone is not considered. Otherwise it will be the angle of the deposit zone.

However all these results have been obtained without any differentiation of the volume of the debris avalanche or the morphology of the environment. That is why two other sets of PCA have been carried out, one to see the impact of the volume and the other one for the morphology of the environment.

II.2.2.3.2. Impact of the volume

As before using the *Microsoft Excel* statistical analysis, volume has an important influence on the behaviour of debris avalanches. That is why three different PCA have been carried out to study the influence of different categories of deposit volume. Due to poor representation of the angles of the drop and deposit zone where these are included, only the six main parameters have been used.

II.2.2.3.2.1. Small debris avalanches

The data set used for small debris avalanches comprised 30 events characterized by six main parameters (Tab.18).

Parameter\Axis	F1	F2	F3
H	16,312	1,207	33,481
L	**26,523**	0,134	**0,017**
V	1,676	**61,909**	21,350
S	**24,728**	1,259	**0,644**
H/L	7,087	**28,816**	42,199
$S/V^{2/3}$	**23,675**	6,674	2,308

Table 18. Variables contribution for small DA

The F1 axis is mainly affected by three parameters H, L and S which are correlated together. However the F2 axis is most affected by V and H/L, whereas under axis F3, L and S are very well correlated.

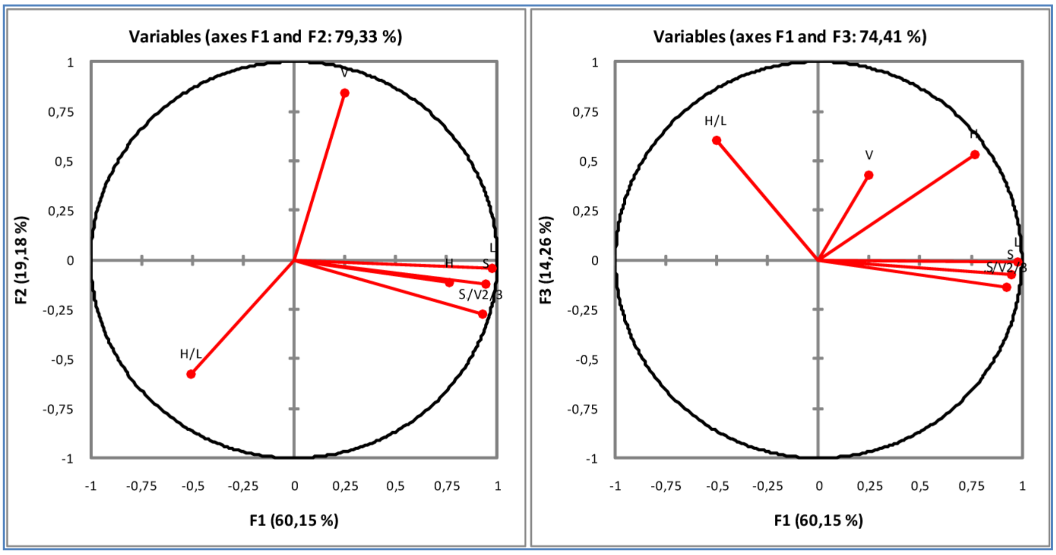


Figure 42. Variables representation for small DA

These representations confirm and complete earlier observations (Fig.42). Under the F1-F2 axis, even if H/L is not very well represented its negative correlation with V is apparent. These two parameters are almost independent of all the others, which are extremely close to the F1 axis. Under the F1-F3 axis no analysis can be done with parameter V as its representation is very poor. However it is possible to see that L, S and $S/V^{2/3}$ are positively correlated and that H and H/L are independent.

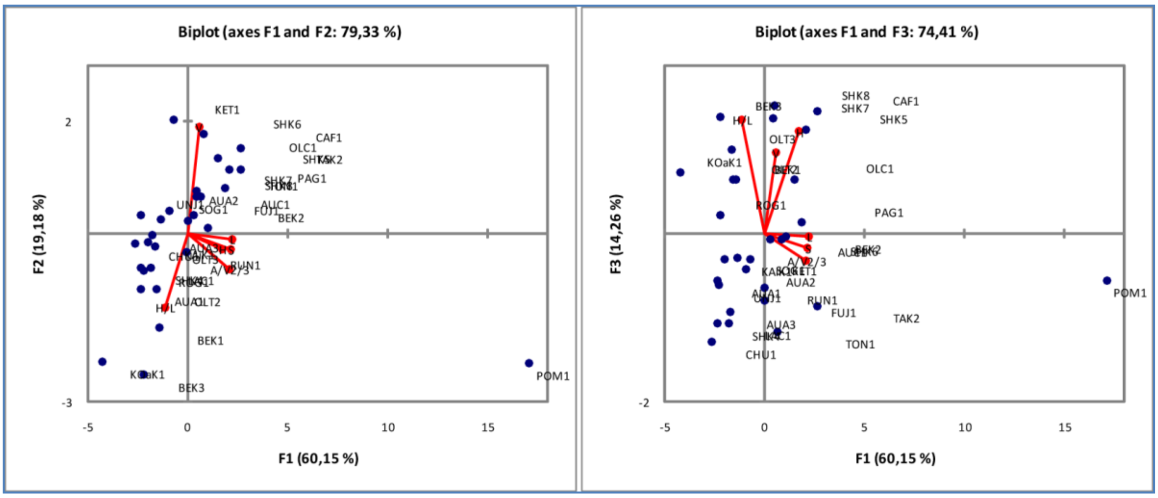


Figure 43. Biplot representation of variables and samples for small DA

On Fig. 43, the importance of H/L and V can been seen, however H might have an influence under the F3 axis. Another interesting thing is that most of the scattered samples are close to the F2 axis for both representations.

II.2.2.3.2.2. Medium debris avalanches

The data set used for medium debris avalanches characterized by the six main parameters is composed of 32 events (Tab.19).

Parameter\Axis	F1	F2	F3
H	16,144	0,203	54,670
L	16,617	**25,897**	4,527
V	14,580	15,281	16,150
S	**21,726**	9,961	4,700
H/L	8,201	**45,409**	19,953
$S/V^{2/3}$	**22,731**	3,249	0,001

Table 19. Variables contribution for medium DA

The first evident is between S and $S/V^{2/3}$ under the F1 axis. Under F2 and F3 axis H/L and L are correlated. However it is difficult to see clear relations without looking at the representation of variables.

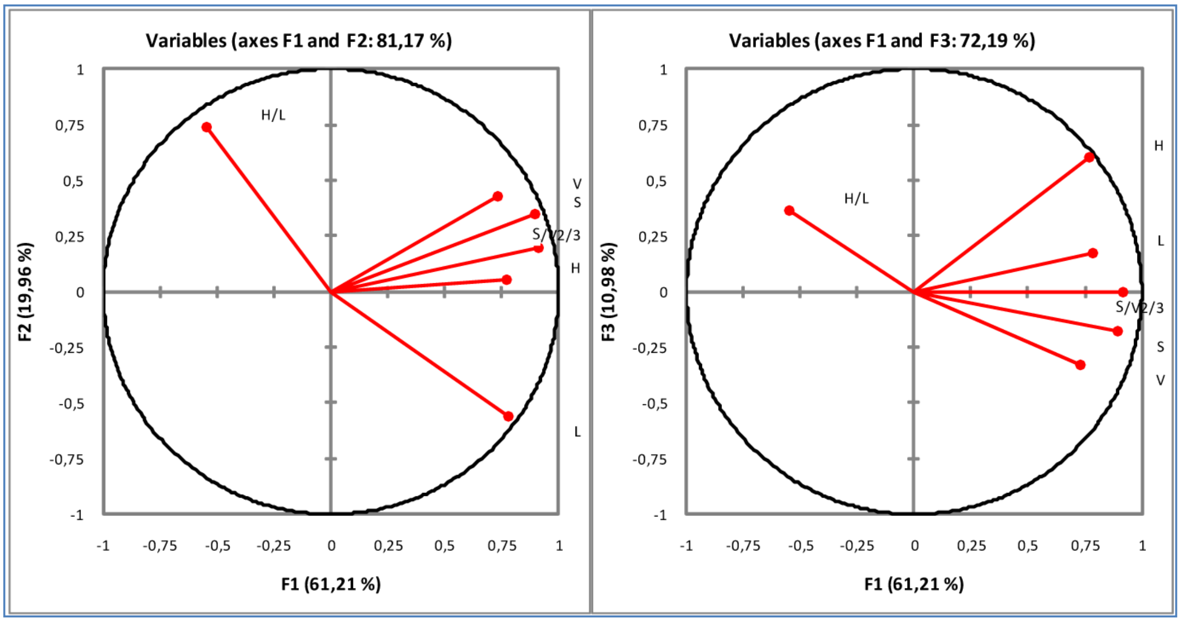


Figure 44. Variables representation for medium DA

The first representation confirms the correlation between S and $S/V^{2/3}$, however H and V are not far away from S but they are less well represented (Fig.44). All these parameters are almost independent of H/L and L which have a negative correlation under the F1-F2 axis. The F1-F3 axis is not very interesting to analyse because of the bad representation of a couple of parameters. However, S and $S/V^{2/3}$ have a positive correlation.

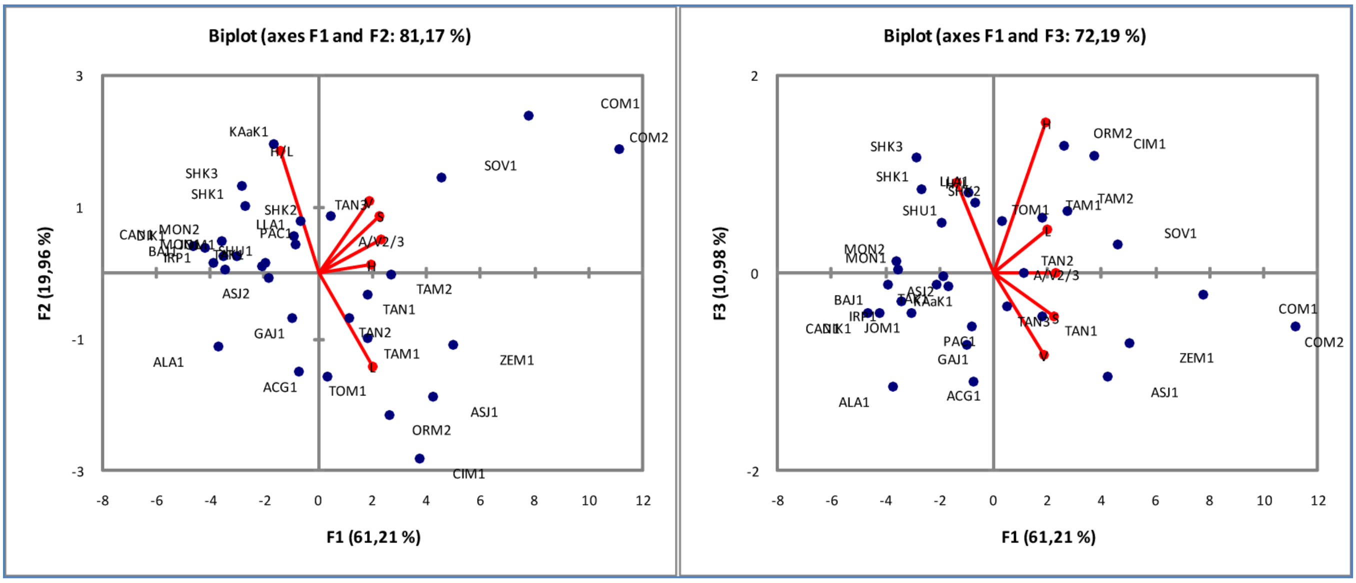


Figure 45. Variables and samples biplots for medium DA

In Fig. 45, samples are scattered in the same vector direction as H/L and also L or V. For medium debris avalanches, samples are much more scattered than for small debris avalanches and it is impossible to determine any particular axis with any affinity with samples.

II.2.2.3.2.3. Large debris avalanches

The data set used for large debris avalanches comprised 13 events characterized by six main parameters (Tab.20).

	F1	F2	F3
H	10,580	52,395	**0,542**
L	**21,978**	8,861	**0,472**
V	9,925	**12,208**	57,243
S	**20,535**	**14,686**	5,586
H/L	**20,496**	0,905	4,012
$S/V^{2/3}$	16,485	**10,946**	32,145

Table 20. Variables contribution for large DA

The F1 axis is dominated by L, S and H/L which are well correlated. The F2 axis shows a correlation between every factor which deals with V, S and $S/V^{2/3}$, whereas L and H parameters are correlated under the F3 axis.

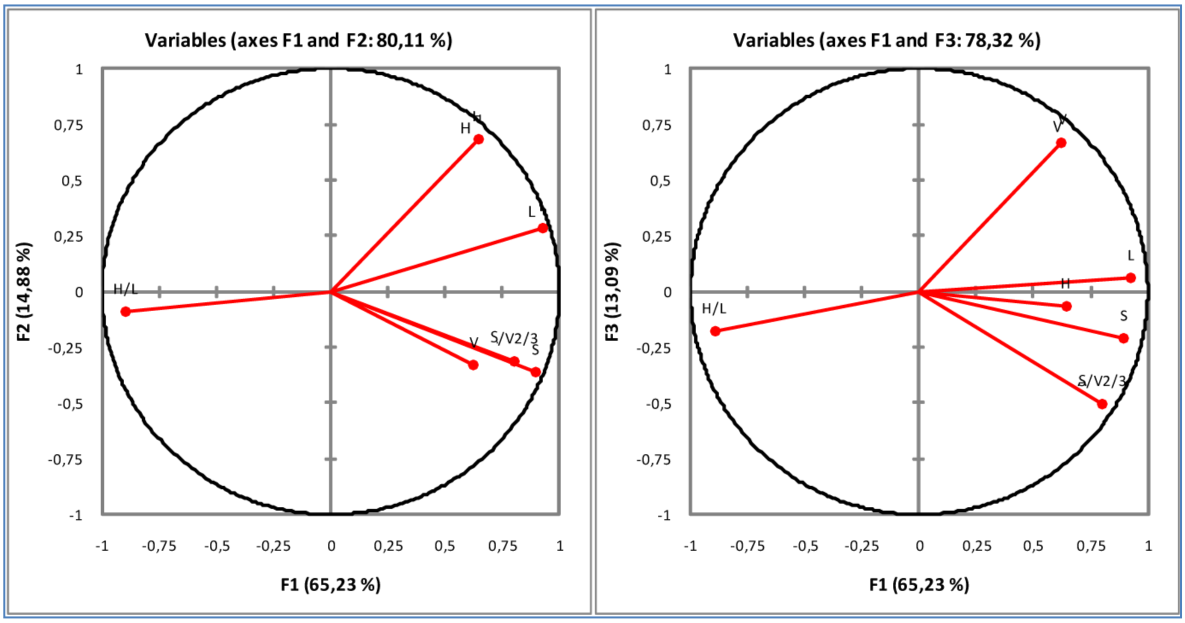


Figure 46. Variables representation for large DA

Representations of the variables show a negative correlation between H/L and L (Fig.46). In both representations H/L is completely apart from other parameters, and the two factors S and $S/V^{2/3}$ are correlated positively.

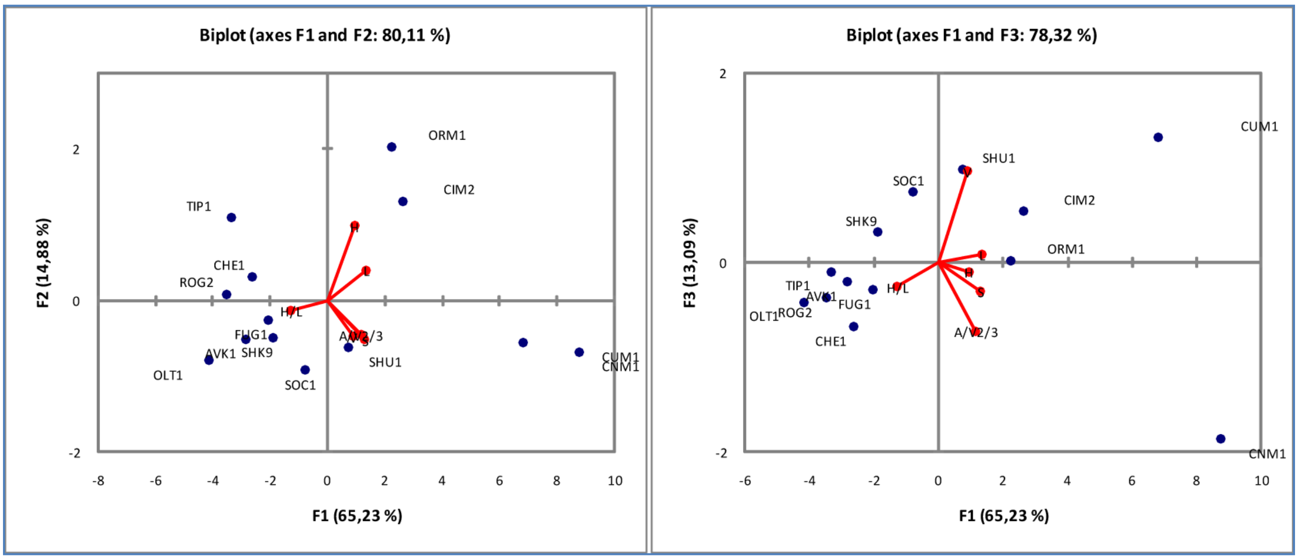


Figure 47. Biplot of variables and samples representation for large DA

The H/L and V vector directions are the two that most affect the distribution of samples for the data set used (Fig.47). As seen for medium debris avalanches, there is no axis with any affinity with sample.

II.2.2.3.2.4. Conclusion

All the results have been summarized in order to have a global view and better understanding of the correlations between these eight parameters with the influence of the volume (Tab.21).

	Positive correlations	Negative correlations	Link with samples
All	L, H, S	H/L, L	H/L, $S/V^{2/3}$
Small DAD	L, S, $S/V^{2/3}$	H/L, V	H/L, V
Medium DAD	V, S, $S/V^{2/3}$	H/L, L	H/L, V or L
Large DAD	S, $S/V^{2/3}$	H/L, L	H/L, V

Table 21. Correlation of each category of debris avalanches regarding the volume

Even though the volume changes, if the deposit surface increases then $S/V^{2/3}$ factor increases. However this relation is linked with the runout for small debris avalanche (if S increases then L increases) whereas it is linked with the volume for medium debris avalanches (if S increases then V increases). This distinction between small and medium debris avalanches is also present for negative correlations. Both involve H/L; however with small debris avalanches, if this factor increases then the volume will decrease, whereas with medium debris avalanches it will be the runout which will decrease. So for small DADs, if H/L decreases then L increases, however for medium DADs if H/L decreases then V increases. Sample distribution is mainly represented by H/L even for samples of different volume. Then the second parameter which represents sample distribution is V, however if the angle of the deposit zone is used then this parameter will be the second one to represent sample distribution. Another observation with the addition of the angle of the deposit zone is that if H/L increases then the angle of the deposit zone increases.

II.2.2.3.3. Influence of the morphology of the environment

As the aim of this work is to see the impact of the morphology of the environment on volcanic debris avalanches, three extra PCA have been carried out to distinguish the effect of morphology by using the classification created for the statistical analysis. For these analyses, the angles of the drop and deposit zone have been omitted because of the poor results that they produced.

II.2.2.3.3.1. Unconfined

The data set used for unconfined debris avalanches comprised 26 events characterized by six main parameters (Tab.22).

Parameter\Axis	F1	F2	F3
H	**20,291**	**0,020**	22,518
L	**25,351**	**1,137**	2,276
V	6,664	59,914	**1,596**
S	**25,244**	**0,513**	**1,657**
H/L	9,369	**1,122**	71,522
$S/V^{2/3}$	13,080	37,294	**0,433**

Table 22. Contribution of the six main variables for unconfined DA

Under the F1 axis, H, L and S are correlated. However the F2 axis is characterized by the distinction of two main parameters V and $S/V^{2/3}$ as all the other parameters have a similar magnitude. The last axis is affected mainly by H/L which has a better correlation with H than L as seen in previous analyses.

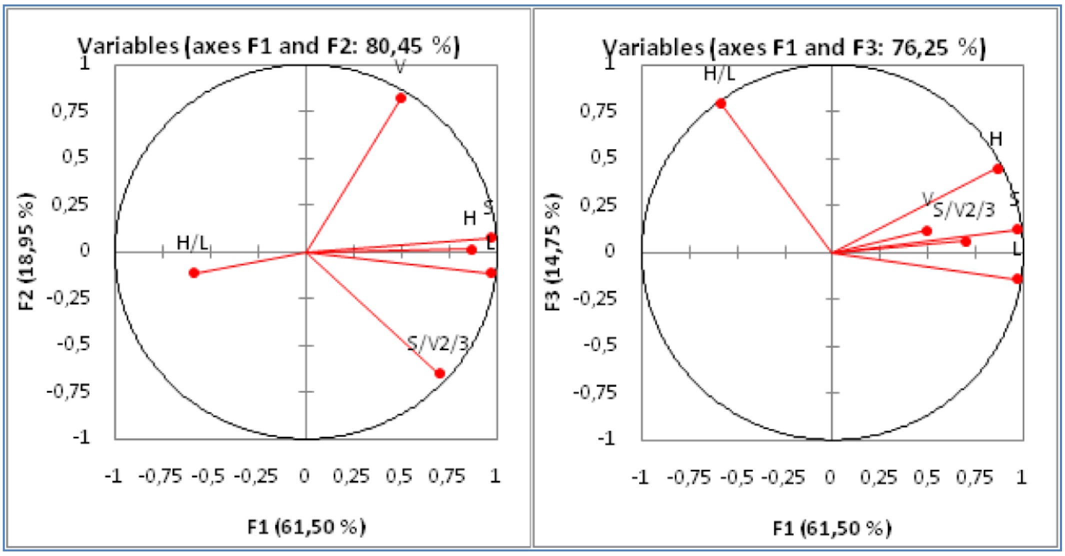


Figure 48. Variables distribution representation for unconfined DA

In addition to the observation from the contribution of variables, it is possible to see that under the F1 axis, V and $S/V^{2/3}$ are independent, whereas H, L and S have a positive correlation (Fig.48). However no analyses with H/L are impossible due to its poor representation. Under the F2 axis, H/L is more definite, and has a negative correlation with L.

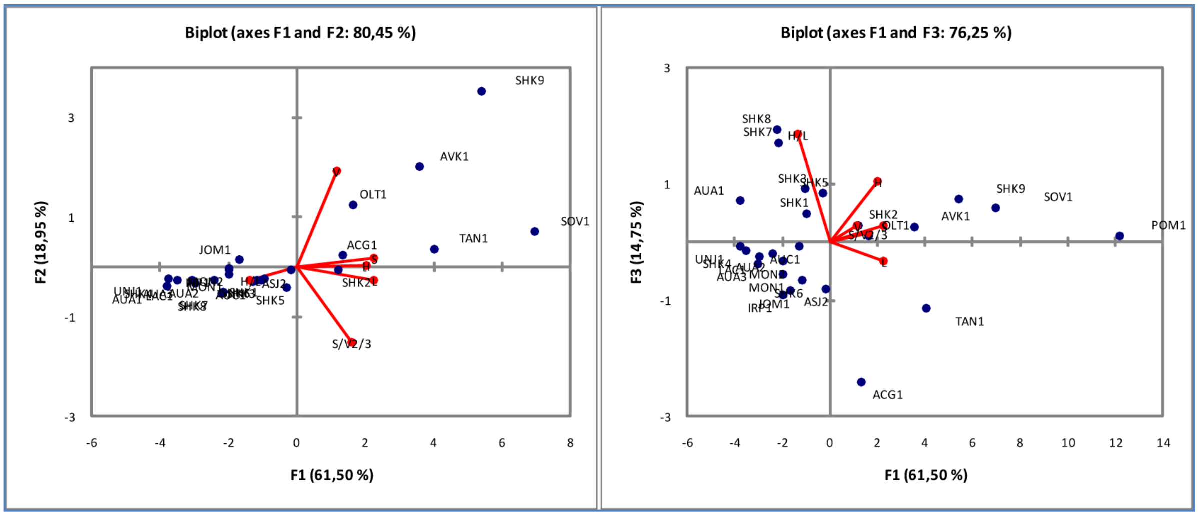


Figure 49. Biplot representation with variables and samples for unconfined DA

Under the F1-F2 or F1-F3 axis biplot representations, most of the samples are scattered in the same direction as the vector of H/L: V might also have some influence according to the distribution of the data (Fig.49).

II.2.2.3.3.2. Semi-confined

Using the same six main parameters, the data set used for semi-confined debris avalanches was made up of nine events (Tab.23).

Parameter\Axis	F1	F2	F3
H	9,336	31,175	35,713
L	**24,612**	**1,704**	**0,032**
V	5,959	48,033	11,826
S	**24,043**	**1,056**	**0,725**
H/L	18,578	**1,657**	32,883
$S/V^{2/3}$	17,473	16,376	18,821

Table 23. Variables contribution of semi-confined DA

Under the F1 and F3 axes L and S are correlated, whereas under the F2 axis L and S are correlated with H/L.

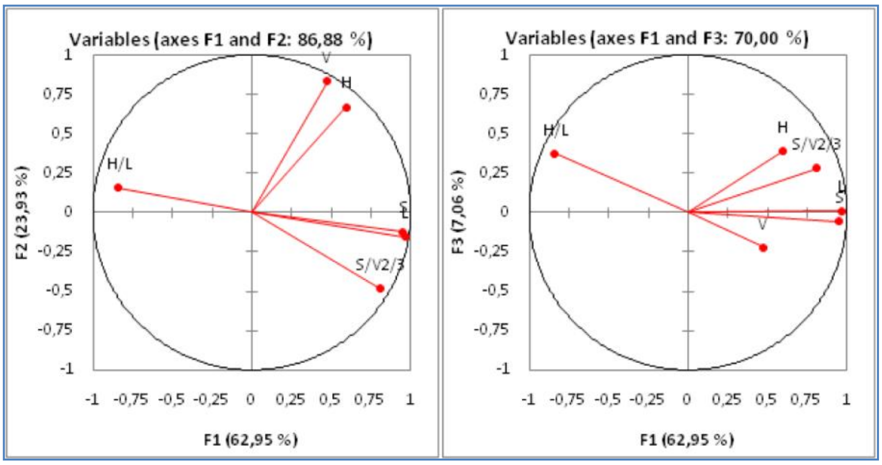


Figure 50. Variables representation of semi-confined DA

The representation highlights the positive correlation between V and H which is almost perpendicular to another positive correlation between S and L (Fig.50). However H/L, L and S have a negative correlation under the F1-F2 axis. Due to poor representation under the F1-F3 axis only a confirmation of the relation between L and S can be done; they are still positively correlated.

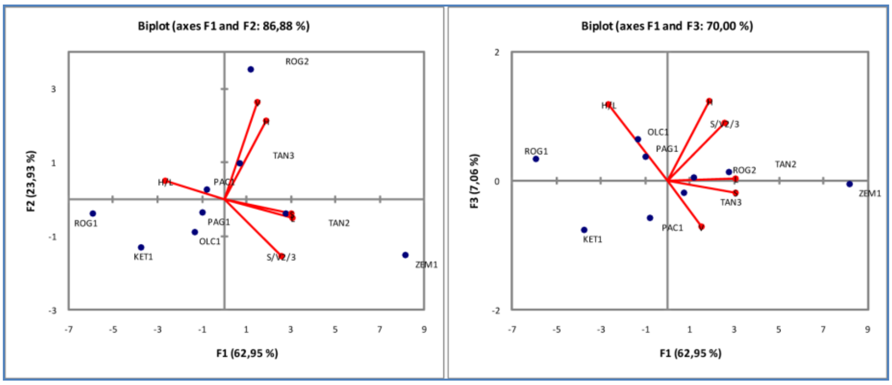


Figure 51. Biplot representation of variables and samples of semi-confined DA

Most of the samples are scattered in the same direction as the vector of H/L and might be affected also by V (Fig.51). However due to the small number of events represented no general tendency of data can be seen.

II.2.2.3.3.3. Confined

The data set used for confined debris avalanches was composed of 32 events characterized by six main parameters (Tab.24).

Parameter\Axe	F1	F2	F3
H	**15,140**	10,877	17,861
L	23,073	**0,009**	7,175
V	**14,838**	33,643	9,672
S	20,351	**0,011**	32,839
H/L	14,053	8,499	24,455
$S/V^{2/3}$	12,546	46,960	7,999

Table 24. Contribution of the six main parameters for confined DA

Under the F1 axis, V and H are very well correlated together even though the distinction between all parameters is not very significant due to small differences. This is different under the F2 axis where L and S are correlated and completely distinguished from other parameter contributions.

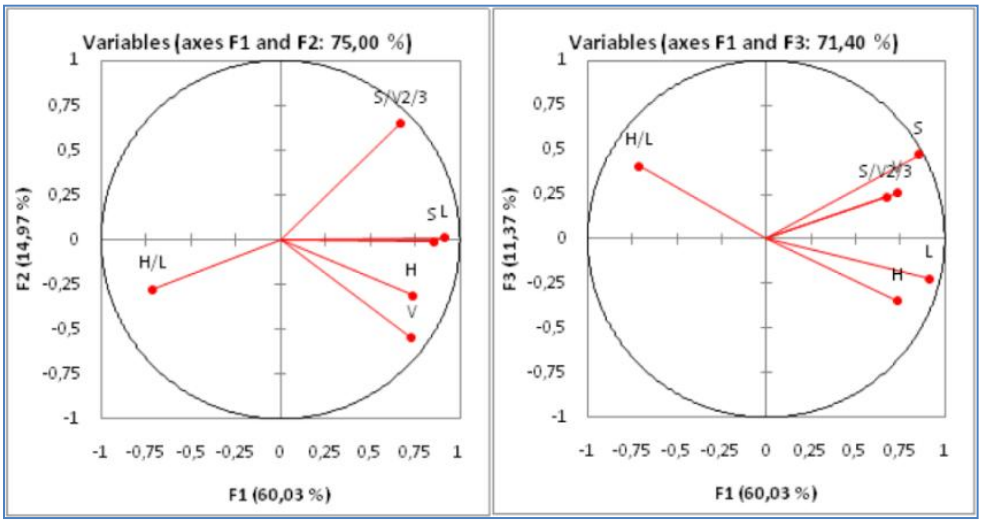


Figure 52. Variables representation for confined DA

In addition with these observations, under the F1-F3 axis H/L and H have a negative correlation (Fig.52).

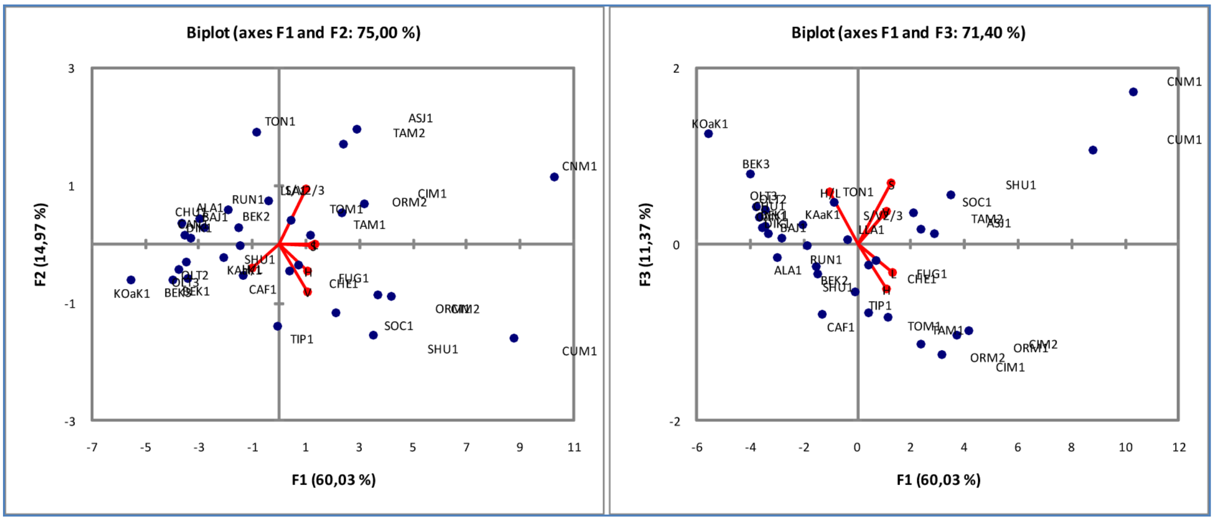


Figure 53. Biplot representation of variables and samples for confined DA

Similarly to the observations for unconfined and semi-confined debris avalanches, most of the samples are scattered in the same direction as the vector of H/L and are a little influenced by V (Fig.53).

II.2.2.3.3.4. Conclusion

All the results have been summarized in order to have a better understanding and global view of the correlations between these eight parameters (Tab.25).

	Positive correlations	Negative correlations	Link with samples
Unconfined	S, L & H	H/L & H, S, L	H/L & V
Semi confined	S, L & $S/V^{2/3}$ and V & H	H/L & L, S, $S/V^{2/3}$	H/L & V or L
Confined	$S/V^{2/3}$, S & L and V & H	H/L & L, $S/V^{2/3}$	H/L & V or H

Table 25. Correlations for every category of debris avalanches considering the morphology of the environment

For all environments, if the surface of the debris avalanche increases then the runout increases. However if H/L decreases then $S/V^{2/3}$ increases. Sample distribution is represented mainly by H/L and to a lesser extent by the volume.

The main difference between unconfined and confined debris avalanches is the influence of the volume. This influence seems to be more important for a confined environment as, if the height increases, then the volume increases. By contrast for unconfined debris avalanches the volume is not part of any correlation. Only height will increase if the surface (and also the runout) increases. This observation, which was found by Martinelli (2005) with a small database, is shown again with these analyses. Another difference is the parameter linked with the mobility (H/L). For unconfined environment the H/L has a negative correlation with S, however this negative correlation evolves with the increase of the confinement. As a matter of fact the more confined and environment gets, the stronger the negative correlation of H/L with $S/V^{2/3}$.

If angles of the drop and the deposit zone are added, then the same observations as those found for a variation of volume are apparent. The only new correlation is the one between H/L and α_2 for all morphologies of environment.

Sample distribution is mainly represented by H/L and to a lesser proportion by V. However if the angle of the deposit zone is included then it represents a smaller proportion of the sample distribution.

II.2.2.4. General interpretations of PCA

After all these observations, it is interesting to try to explain them and draw conclusions. However it is important to keep in mind that any analysis can be improved and that the links pointed out between variables are not cause to effect relation.

II.2.2.4.1. Interpretation

For every analysis carried out using the angle of the deposit zone, a positive correlation has been found with H/L. In other words, if H/L decreases then the angle of the deposit zone decreases. So it seems then that the angle of the deposit zone and the mobility of the debris avalanche are linked somehow together, and that the steeper the angle, the greater the mobility. The obvious explanation is be that the downslope component of gravity will help the debris avalanche to keep moving whereas on a horizontal surface the gravity force will act only to mobilise friction and cause deceleration. This result is logical and shows that the statistical analysis corresponds with physics. This does not mean that high mobility is always due to steep deposit zone; however steep deposit zone is a factor which helps to increase the mobility.

Category	Positive correlation	Negative correlation
Volume	S, $S/V^{2/3}$	H/L, L
Morphology of the environment	S, L	H/L, $S/V^{2/3}$

Table 26. General relations from PCAs

For analyses considering the three categories of volume, if the surface increases then $S/V^{2/3}$ will increase (Tab.26). From a mathematical point of view this relation is logical as an increase of the surface, even if it is smaller than the volume, will increase $S/V^{2/3}$. The second relation for the volume is a negative one between H/L and L. To put it differently if H/L decreases then L increases. This relation is also logical from a mathematical aspect, as an increase of the denominator causes a reduction of the value. So the influence of the volume on volcanic debris avalanches parameter relations is well described by mathematical relations.

However relations obtained with respect to the morphology of the environment are quite different. Some similarities with relations obtained from the volume are present, such as the fact that the surface area is still one of the parameters present with a positive correlation and that H/L is still has a negative correlation. The only difference is between $S/V^{2/3}$ and L: they have the opposite tendency to that for the volume. For instance, if L is the second parameter of the negative correlation for the volume category, then it will be part of the positive correlation for the category of the morphology of the environment. So for the morphology of the environment, if the surface area increases, an increase of the runout is observed. This shows that the mobility of the debris avalanche has a direct impact on the geometry of the deposit. This observation was made by Martinelli (2005), however she showed that for confined events if the runout increases then the surface area decreases. An explanation of this tendency can be the thickness of the deposit. With the same volume of debris avalanche, if the thickness decreases with the increase of the runout, this could cause a reduction of the surface of the deposit due to reduced flow width. This hypothesis can be verified by the use of analogue modelling. However it is important to keep in mind that for this study, different volumes have been considered at the same time.

So the difference between the volume and the morphology of the environment is mainly shown by two main parameters: the runout and $S/V^{2/3}$.

Category	Positive correlations	Negative correlations	Link with samples
Unconfined			
Small	L, S, $S/V^{2/3}$	H/L, L	V, H/L
Medium	S, $S/V^{2/3}$	H/L, L	H/L, V or L
Confined			
Small	$S/V^{2/3}$, S ; L, V, H	H/L, V	H/L
Medium	H, L ; $S/V^{2/3,}$ S	H/L, L & $S/V^{2/3}$	$S/V^{2/3,}$ H/L
Large	$S/V^{2/3,}$ S	H/L, L & $S/V^{2/3}$	H/L

Table 27. PCAs general relations of different categories

This time the two categories have been put together, and it is surprising to notice that the positive correlation between S and $S/V^{2/3}$ is present for all categories (Tab.27). So the volume definitely has an impact even if the morphology of the environment is considered. This influence is stronger than the influence of the morphology of the environment with all volumes as the positive relation between the surface area and the runout is not present any more. Regardless of the volume categories, relations between parameters are the same for unconfined events. These relations are similar to these found when only the three main categories of volume were considered. The main interpretation of this observation is that for an unconfined environment, the volume has no major influence on parameter relations. As a result the parametric relations for a small debris avalanche will be the same as those of a medium one.

However, apart from having slight differences from unconfined debris avalanches, confined events are quite different with respect to the volume categories. So for confined areas, volume does have an influence on parameter relations. Confined debris avalanches are characterized by one more positive relation than unconfined ones: if height increases, then the runout increases. This relation is quite logical from geometry:

$$\tan\alpha = \frac{H}{L} \leftrightarrow H = L.\tan\alpha$$

With H: height, L: runout and α angle of the line from the deposit zone to the drop zone with the horizontal.

So as a matter of fact, for an equal angle α if height increases then the runout increases as well. The difference between small and medium confined debris avalanches is due to the volume. Actually the volume is present in positive and negative relations only for small debris avalanches. Its influence on other parameters is important only below a certain limit which seems to be $1km^3$. As seen before, if height increases then the runout increases, however for small confined events the volume increases as well. Does this observation mean that in case of confined environment, up to a certain value the volume affects the runout and above this value something else affects the runout? The fact that small debris avalanches are more likely to be affected by volume change than the topography is logical because a too small volume cannot be affected by topography; however once this volume is large enough then it is more likely to be affected by the topography than by a volume change.

The main difference between unconfined and confined events is that for unconfined areas the runout is positively correlated with the surface area whereas for confined areas the runout is not correlated at all with the surface. This observation might be due to the fact that in a confined environment the surface area of the event will be controlled by the environment. As a result, if the runout has a positive correlation with the surface, then if the surface is modified due to external influences the runout cannot have the same correlation with the surface.

II.2.2.4.2. Improvements and complementary analysis

As noted above the first improvement that can be done is to have the same error determination for a parameter of each event. This will be possible only when a general agreement is reached about methodology and tools used. In addition, the determination of the angle of the drop and the deposit zone need to be much more precise. Of course, increasing the volume of data will be an improvement, but it would be best to have the same proportion of each kind of parameter of the debris avalanches. This means for example, the same proportion of events in every category of angle or size.

To complete these analyses, further parameters might be added such as the average thickness and the incorporated material from the substratum by the avalanche. It would be also interesting to see if there is any effect due to the nature of the environment (e.g. subaerial, extraterrestrial or marine).

II.2.3. Multiple regressions

Multiple regressions were carried out in order to quantify the results obtained from PCA. This explicative method will be first introduced then the methodology used explained before presenting the results.

II.2.3.1. Principles

A multiple regression is a statistical tool which explains a numerical variable by several other independent ones. This is useful if the aim is to predict the value of a variable and to quantify the importance of explicative variables to the variable in question.

For this, a model which represents a regression is calculated and characterised by an equation such as:

$$Y = a + b_1X_1 + b_2X_2 + b_3X_3 + ... + b_nX_n$$

where Y is variable to be explained, X is an explicative variable, and a and b are coefficients of regression.

This equation is accompanied by two main parameters. The first is the ***coefficient of multiple correlations R***, which measures the link between the target variable and explicative variables. The second is the ***adjusted coefficient of multiple determinations*** (***adjusted R²***) which gives the percentage of variation of the variable that is explained by the explicative variables.

However as in most statistical analyses, several conditions must be respected. As this method is based on the hypothesis of parametric statistics, two main conditions exist:

1. Make sure that the model is precise enough. For that the explicative variables have to be independent of each other.
2. Be sure that the quality of the model is acceptable. Three main tests of this can be carried out. First, are R and adjusted R^2 close to 1? Second, use the Fisher test to check that the quality of the sample adjustment is good (F must be close to zero).

Thus the closer R and the adjusted R^2 are to 1, and the closer F is to zero, the better the model.

II.2.3.2. Methodology

The first task was to select the parameters to explain. From the PCA analysis three parameters appeared of interest: L, S and V. They are especially interesting as they are the elements involved in the determination of the area at risk. Next, explicative variables were chosen. As they have to be independent only one variable was used at the same time. For each regression, every condition has been satisfied.

General	All	65
Morphology of the envionment	Unconfined	26
	Semi-confined	9
	Confined	30
Volume	Small	24
	Medium	28
	Large	13

Table 28. Amount of data per category used

As the aim is to quantify results from the PCA, the same categories of the morphology of the environment and the volume were used, however a general analysis has also been carried out (Tab.28). Results obtained from *XLSTAT* software are presented in a table with explicative variables, adjusted R^2 and also the error percentage known with Fisher test.

II.2.3.3. Analysis

Results are presented into three different tables, one for each target variable in order to help the understanding and correlation.

II.2.3.3.1. L as target variable

The first variable to be explained is the runout L using four parameters (Tab.29):

Variables		V	H	α_1	α_2
General		0,299	***0,502***	0,153	0,138
Morphology	unconfined	0,089	***0,589***	-0,007	0,124
	semi-confined	-0,019	0,090	***0,343***	0,153
	confined	0,294	***0,509***	0,295	0,140
Volume	small	-0,031	***0,723***	0,005	0,170
	Medium	0,015	***0,390***	0,170	***0,189***
	Large	0,162	***0,466***	0,164	-0,091

Table 29. Adjusted R^2 obtained for L as the variable to explain

The adjusted R^2 have different values for different categories of debris avalanches, however most of the highest values relate to one main variable: height of the drop H. Adjusted R^2 values for unconfined and confined situations are not very different (8%). On the other hand, R^2 values are significantly different depending on the volume of the event; (33% between small and medium debris avalanches). For both cases, highest values are found for unconfined, small events which are well explained by the height of drop (at least 70% for one variable), whereas confined, medium debris avalanches are not very well explained by this variable (a maximum of 50%).

II.2.3.3.2. S as a variable to explain

The second variable considered is the surface area S using four parameters (Tab.30).

Variables		V	H	α1	α2
General		***0,478***	0,271	0,038	0,014
Morphology	unconfined	0,251	***0,769***	-0,018	0,045
	semi-confined	0,043	0,045	***0,279***	0,202
	confined	***0,504***	0,192	0,067	-0,014
Volume	small	-0,035	***0,427***	0,032	0,137
	medium	***0,414***	0,207	0,081	0,055
	large	***0,262***	0,073	-0,058	-0,069

Table 30. Adjusted R² obtained for S as the variable to explain

Adjusted R² values differ for different categories, however most of the higher values relate to one variable: the volume. The second relevant variable is the height of the drop that has an impact for some of the categories of debris avalanches. Values of adjusted R² relating to the morphology of the environment and the volume are quite different (48%). For both cases, highest values are found for unconfined, small events which are well explained by the height of drop, whereas confined, medium debris avalanches are not very well explained by this variable but rather by the volume.

II.2.3.3.3. V as target variable

The last variable to be explained is the volume V with the use of three parameters (Tab.31). However it is important to keep in mind that this variable is independent and determined before the beginning of the avalanche.

Variables		H	α1	α2
General		***0,262***	0,093	-0,012
Morpholo	unconfined	***0,174***	-0,024	-0,020
	semi-confined	***0,436***	-0,130	-0,143
	confined	***0,239***	0,228	-0,028
Volume	small	***0,087***	-0,027	***0,199***
	medium	0,040	***0,100***	0,046
	large	-0,043	0,104	***0,111***

Table 31. Adjusted R² obtained for V as the variable to explain

Regarding the used, the adjusted R² values differ for different categories of debris avalanches, however most of the higher values relate to the height of drop. This means that the volume has the most influence on the fall height. Then α_1 and α_2 affect the volume depending on the category of the debris avalanche. Adjusted R² values for unconfined and confined environments for the highest value found with the fall height differ by 6.5%. Repeating this analysis for the volume of the event, the difference is slightly greater (8.8%). However all these observations are limited by the fact that the correlations are very slow (less than 26% if the semi-confined avalanches are not considered).

II.2.3.4. Interpretation

Semi-confined and large debris avalanches are less well explained as they are less well represented than the others. In order to illustrate the impact of each category, Table 32 summarises the highest adjusted R² values.

Variables		L		S		V	
General		0,506	H	0,478	V	0.262	H
Morphology	unconfined	0,589	H	0,769	H	0.174	H
	semi-confined	0,343	α_1	0,279	α_1	0.436	H
	confined	0,509	H	0,504	V	0.239	H
Volume	small	0,723	H	0,427	H	0.199	α_2
	medium	0,390	H	0,414	V	0.100	α_1
	large	0,466	H	0,262	V	0.111	α_2
Average		***0.503***		***0.448***		***0.217***	

Table 32. Highest adjusted R² values and their explicative variables for the three variables to be explained

The first point to note is that although a maximum of four variables were used to explain the target variable, often only two variables are present in most correlations: the height of the drop and the volume. On average, the runout and the surface area are much better explained than the volume, albeit more scattered. This might be due to the fact that the volume is an independent variable and is influenced by other parameters that were not represented here such as the degree of alteration or volcanic composition. However the best target variable explains just 50.3% on average. This means that the explicative variables used do not explain most of the target variable and some other explicative variables should be used to complete the study.

The second point is that results fall into two main categories, the first related to the adjusted R² value (highest vs lowest values) and the second related to the explicative variables. These two categories are linked together as they characterized the same types of debris avalanches, (unconfined/small and confined/medium). It seems logical that small debris avalanches can show the same behaviour as unconfined ones as their volume will be less affected by external factors such as the morphology of the environment, compared to medium ones.

Looking more deeply into these results, the runout of small and unconfined debris avalanches is explained by the fall height (72.3 and 58.9%), whereas medium and confined one are less well explained by the same variable the height of drop (39 and 50.9%). It is remarkable that one single variable can explain up to 72% of another one. The relation with the height of the drop seems quite intuitive. It is interesting to notice that the differences of adjusted R^2 values are higher regarding the volume of the avalanche (33.3%) than the morphology of the environment (8%). Small avalanche runouts are more explained by the fall height than medium avalanche runouts. However a difference of the topography does not affect the impact of the fall height to explain the runout.

The surface is explained by two difference explicative variables the fall height and the volume. The two same groups of variables are present: the first group is composed small and unconfined avalanches whereas the second one is comprised of medium and confined avalanches. Small and unconfined avalanche surfaces are explained by the fall height (42.7 and 76.9%) but medium and confined avalanche surfaces are explained by the volume (41.4 and 50.4%).

Two categories of avalanche can be defined: small/unconfined and medium/confined. Thus the environment of the deposit definitely has an impact on debris avalanche deposit characteristics, and so does the volume.

III. General conclusions

III.1. Analysis with two variables

Data must be chosen very carefully otherwise analyses can be biased and lead to misinterpretation; this may have been the case for the Hayashi and Self database.

- As expected the behaviour of debris avalanches depends on their volume; the bigger the avalanche, the bigger are H and L.
- The presence in the data of large debris avalanches has an influence on the results, as correlations alter when large debris avalanches are removed. However, small and medium events (particularly the latter) are more affected by the morphology of the environment.
- As expected there is no correlation between the angle of the drop zone and that of the deposit zone, and it has been confirmed that deposits tend to be found in areas of low slope angle.
- One of the main results is that there is a relation between the runout, the mobility and the slope angle of the deposit zone. The bigger the runout, the bigger the mobility and the lower the deposit slope angle.
- A second result is that a link has been found between the morphology of the environment and the shape of the deposit; some shapes appear to be very specific to a particular type of morphology.
- And the third one is that the runout seems to depend on the morphology of the environment. Confined events tend to have highest values for the runout.

III.2. Analysis with more variables

Results obtained from PCA confirmed what was already known - that L and H are positively correlated and that the addition of the surface area reduces the effect of the relation between these two parameters and the volume.

However new relations were apparent from PCA, such as the positive correlation between H/L and the angle of the deposit zone. Samples tend to be aligned mainly with respect to H/L and with a less important influence from the volume. In addition, the morphology of the environment and the volume have different impacts on debris avalanche parameters. The volume affects small debris avalanches in confined environments; by contrast it has no impact on unconfined events.

These observations were complemented by multiple regressions which showed that mainly H and V explain 50% of the three main characteristics of debris avalanches L and S. The best results were obtained for L which seems to be mainly (50.3%) due to the fall height. Volume is a less well explained variable and the only one which is related to the slope angle of the deposit; no major difference between unconfined and confined debris avalanches was observed.

Another result was the fact that debris avalanches can be divided in two main categories with similar behaviours; unconfined and small debris avalanches, and confined and medium ones.

III.3. Relations

These results complement some previous studies such as that of Nicoletti and Sorriso-Valvo (1991) concerning the shape of the deposit. Their study dealt with the influence of the morphology of the environment on deposit shape and mobility of non-volcanic debris avalanches; it showed that the shape of the deposit is controlled by the environment. This study has shown the same with non-volcanic debris avalanches, but with slightly different outcomes. For volcanic debris avalanches specific shapes are observed only with two morphological features: confined and unconfined. It has also been found that the morphology of the environment has no impact on the runout as values were similar with both unconfined and confined areas. As some small variations were observed with these statistical analyses, analogue modelling will be used to better define this observation (see chapter III).

The main results can be summarized with respect to the category of the debris avalanches (Tab.33).

Category	Unconfined/Small	Confined/Medium
Values of L	Smallest	Highest
Correlation of L	well with H	quite well with H
Deposit shape	Lobate, fan-shaped or digitate	Elongate or winding
Influence on L	mainly V	Mainly the morphology

Table 33. Main observations regarding the two categories

It seems that the volume and the morphology of the environment have the main impact on the runout. However the runout is much better explained by the height of drop than by the volume; and when the surface area of the deposit is introduced the relation of the volume with the runout and height of drop is less important. The deposit's surface area depends on the morphology of the environment, which might indicate that the environment has more influence than the volume on geometrical characteristics of the deposit.

To verify and test these observations and results, experimental modelling will be carried out as some parameters can be varied under controlled conditions to see their impact. This is the aim of the next chapter.

Chapter 3. Modelling

Modelling is a technique used to represent an event. This technique has important applications in different fields of sciences and geosciences. It can be achieved by the use of several different tools: analogue, numerical or statistical. These tools or methods are either part of physical modelling (something that can be touched and changed by hand such as sand-box experiments) or non-physical modelling (something that takes place in an artificial environment such as a numerical simulation).

For this study, in order to complement the statistical analyses, analogue and numerical modelling have been used. These two techniques will be first introduced before presenting the analogue modelling carried out for this study and its results. Then the numerical modelling done for this study with the use of *Volcflow* software will be presented.

I. Introduction to modelling

Only two kind of modelling have been used for this study; and will be presented, first the laboratory analogue modelling one then the numerical modelling.

I.1. Laboratory modelling

The laboratory modelling (also called analogue modelling) is used to represent with real materials an in that case a natural event at laboratory scale.

I.1.1. General knowledge and aim

The aim of analogue modelling is to study an event at experimental scale. Laboratory experiments consider the variables that affect the behaviour of the phenomenon and identify a number of dimensionless groupings of variables (by the use of Buckingham's Pi theorem) that must be identical in the two different situations (natural and experimental) and therefore have similar properties (geometrical, kinematical and dynamical) and behaviour (Sanford, 1959; Davies and McSaveney, 1999).

In geology the main concern is to represent events occurring at large time and spatial scales (billions of years and millions of kilometres) at a laboratory and human scale (few hours and meters) that obeys accurate rules. Analogue modelling is now widely used in volcanology and many other fields in order to test interpretations and hypotheses regarding processes derived from geological data. This method provides insights into the basic operating mechanisms; this is why it often implies a simplification of the natural event (Belousov et al, 2005; Martinelli, 2005).

I.1.2. Historical events

Laboratory modelling started at the beginning of the 19^{th} century and has since been modernized; it has been used extensively, but in modern science is often considered inferior to numerical modelling. This is regrettable, because an analogue model is always driven by the laws of nature that drive the full-scale phenomenon, while a numerical model obeys laws prescribed by its programmer. Several geologists have tried to explain observed geological structures by making models using simple materials. The first was James Hall who tried in 1815 to represent the creation of folds in sedimentary layers provoked by an external force. However, the most famous of these analogue modellers is Henry Cadell who developed in January 1887 his own series of experiments to mimic geological fan-structures (Fig.54).

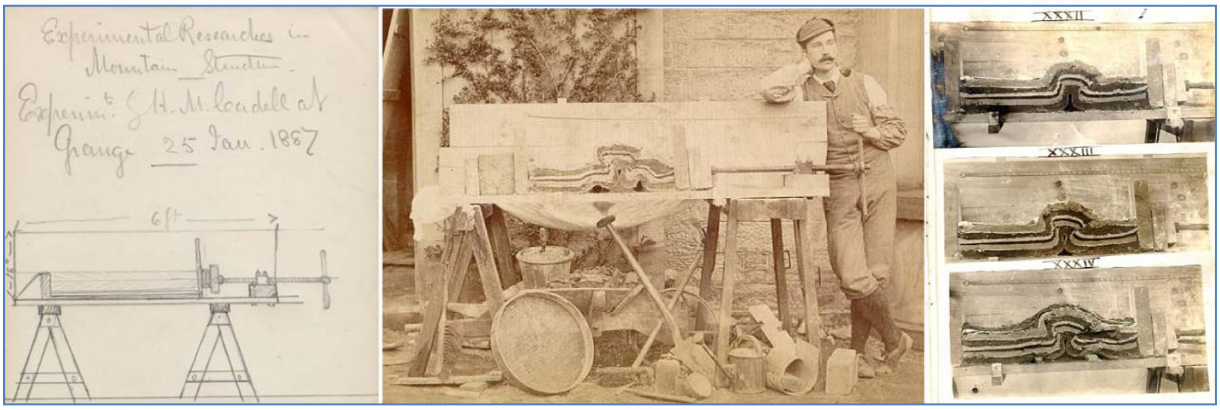


Figure 54. Henry Cadell's modelling showing that fan-structures are formed by compression along the layering (From the British Geological Survey).

At the beginning of analogue modelling, no dimensional ratios were used in laboratory modelling; this is the reason why nowadays scientists talk about analogue modelling instead of laboratory modelling.

I.2. Numerical modelling

Numerical modelling (also called numerical simulation) is another technique to represent an event but compared to analogue modelling this representation is 'artificial'; it depends on the realism of a numerical routine.

I.2.1. General knowledge

A numerical simulation is the 'artificial' reproduction of a phenomenon on a computer. This tool is used in many fields and for several purposes (such as pilots' flight training). However, as soon as it is used for research to represent a complex phenomenon, these simulations are called "modelling". This technique can be defined as the adaptation of mathematical modelling from a theoretical model and the result is often visualized by a graphical interface.

Three main categories of simulation are:

- Continuous simulation – the aim is to analyse the model with variables that have continuous variations in order to predict the system at a selected future moment.
- Discrete simulation – this simulation, usually used for simple principles for a large-scale system, is composed of a succession of events that change the model. It can be a time-slicing model where only the time unit changes, or an event-sequencing where event after event are simulated.

- Simulation by agents – the system is divided into several entities that interact together. Usually it is used for economical and social sciences.

Even if this tool is fast, easily modified, space-saving and cheap, it is important to keep in mind that it is the result of assumed parameters and artificially-created mathematical models. So if the reasoning is false, then the mathematical model is false and simulation results will be incorrect. It does not necessarily represent reality and a critical mindset is essential to assess the results of such models.

I.2.2. Historical events

The first numerical modelling carried out was during World War II in order to model the nuclear detonation process of the Manhattan project. This modelling was possible because of discoveries made in informatics. However the first 'civil' modelling used for a research field was in 1953 in nuclear physics. This experiment, called Fermi-Pasta-Ulam, explored the thermalization process of a solid by the use of the Maniac computer and demonstrated a new field of physics: the nonlinear one.

Since then, many codes have been created in geosciences such as the *Volcflow* code that has been used for this study and is explained below (Fig.55).

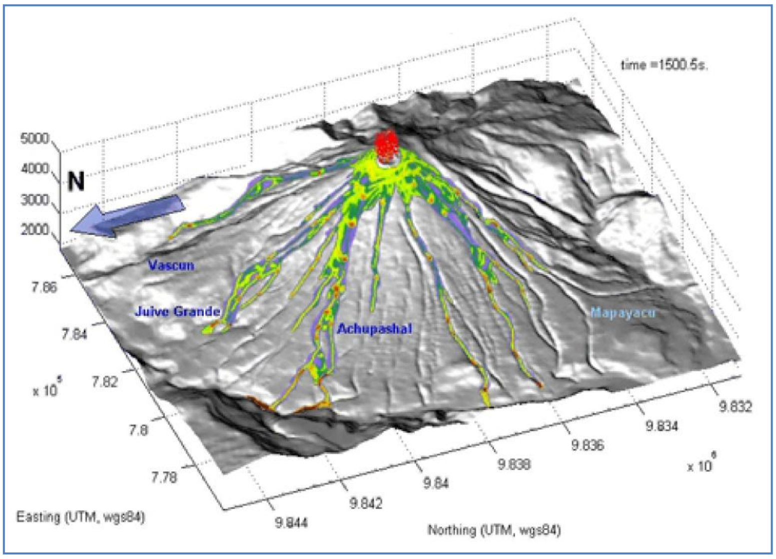


Figure 55. Example of numerical modelling from Volcflow, simulation of a pyroclastic flow at Tunguraha volcano (Kelfoun et al., 2009)

Both of these modelling types have been used to represent volcanic debris avalanches occurring in different environment morphologies and are described below.

II. Analogue modelling

II.1. Aim

This modelling study has been carried out in order to study how the geometry of deposit varies with different parameters and to see if general tendencies can be highlighted. Different sets of experiments have been done, each one of which is focused on one specific parameter. These results will be compared with those from the statistical analyses.

As the study is focussed on the deposit geometry (shape and runout) produced by different environments, the physical processes of debris avalanches will not be studied and the model does not need to perfectly represent the physics of the flow. However this model is similar to the physical processes on which the *Volcflow* code (Shea and Van Wyk de Vries, 2008) is based.

II.2. General settings

The phenomenon to be reproduced is a dry granular mass flow moving down a solid slope under gravity and spreading and translating across this plane, on reaching the lower angle plane at the foot of the slope (Davies and McSaveney, 1999). Thus the materials used for the debris avalanche and the environment are important, as well as variables.

II.2.1. Material used as the environment

After considering several models used for volcanic debris avalanches, the concept developed by Shea and Van Wyk de Vries (2008) has been selected and modified for the purpose of this study. Although this model has only been used once before, the results were good enough to match with previous studies (Fig.56).

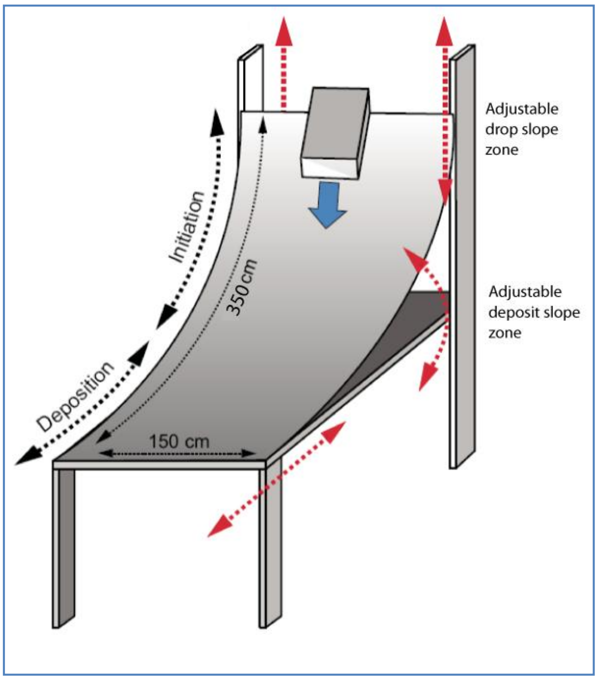


Figure 56. General model (Modified from Shea and Van Wyk de Vries, 2008)

This model has the advantage that the angle of the sliding slope is not constant over the entire pathway. It reduces gradually, which is closer to a volcanic environment and avoids having an abrupt change of slope. In practice, this model allows easy alteration of the slope angles of the drop and deposit zones.

In order to avoid electrostatic effects, the ramp was made of flexible aluminium instead of wood or Plexiglas; the basal friction angle of the aluminium is 24° (Shea and Van Wyk de Vries, 2008). To avoid as much as possible any vibration created during the drop, a rigid platforms supported the model.

The ramp was modified by addition of different features to create different morphologies of the environment. These were made of polystyrene. A total of 6 different environments were used (Fig.57).

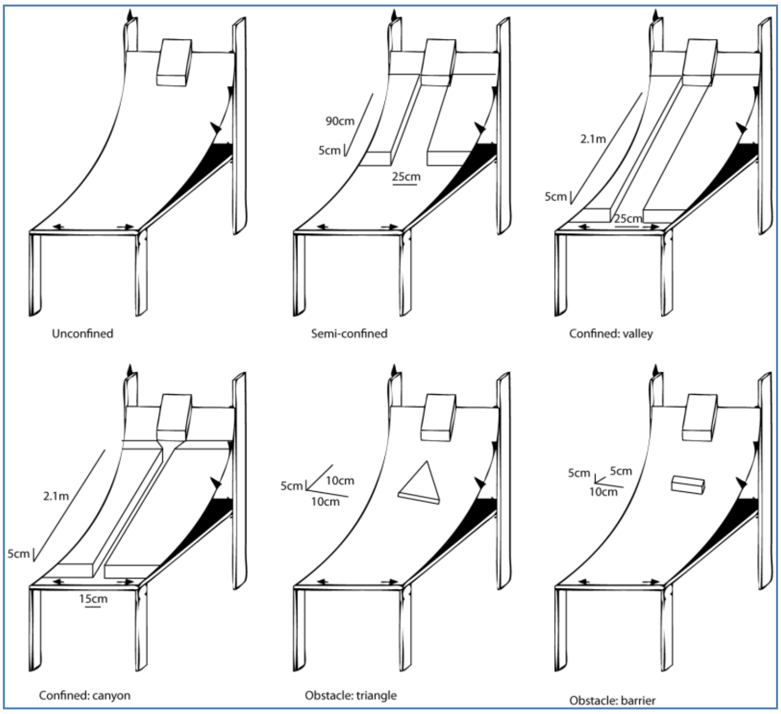


Figure 57. Representation of the six different morphologies of the environment

Below a sandbox fixed at 1m elevation above the bottom of the model with an initial angle of 40°, the profile slope has an equation of a polynomial type:

$$\boxed{y = ax^2 + bx + c}$$

For H=76cm, a=0.0014, b= - 0.6909 and c=86.136

II.2.2. Material used as debris avalanche

The first concern was to select the material that should be used to represent debris avalanches. This must act as a granular mass flow which means large solid grains with less-dense intergranular liquid or gas moving in unison deforming as it is travels dowslope (Iverson and Vallance, 2001).

In earlier works two main materials have been used: bentonite and sand. Bentonite was used by Hsü (1975; 1978), and sand has been widely used. Bentonite has a grain size less than 100µm (Lapides and Yariv, 2004) whereas sand particles vary between 80 and 600µm. However it is well known that particles smaller than 100µm are classified as powder, which means that their behavior (such as electrostatic interactions and humidity effects) differs significantly from that of larger dry granular materials (Shea and Van Wyk de Vries, 2008).

Thus sand was chosen for debris avalanche modeling. It was sieved before use in order to eliminate particles smaller than 100µm. Sand is known to have an internal friction angle similar to most natural material (30°). Cohesion of the material was modified by adding some plaster, a cohesive powder material (Martinelli, 2005; Shea and Van Wyk de Vries, 2008) to achieve the required cohesion ratio.

II.2.3. Scaling and variables

A realistic model must be geometrically similar (so it is a geometric replica of the original, in our case a reduced one), kinematically similar (corresponding particles are found at corresponding points at corresponding times) and dynamically similar (constant ratio between various kind of mechanical forces) to the original (prototype) (Ramberg, 1981). To satisfy all these conditions, scaling follows the Π-theorem. However as our analyses will be focused only on geometrical parameters the use of the Π-theorem is not necessary and only dimensionless numbers by ratio will be introduced. The only important scaling concern is to make sure that geometry of the different elements is similar to those of the prototypes.

However scaling is not the only important element used to define an analogue modeling, the variables are also important. As a matter of fact, scaling cannot be done without variables characterizing the experiment. These variables define the granular mass flow that is about to be reproduce and have to be adapted to the laboratory scale (Tab.34).

Variable		Dimension	Nature	Model
H	Height of fall	m	$0{,}5.10^3$ - 5.10^3	0.33 – 0.76
L	Runout	m	1.10^3 - 120.10^3	---
S	Surface of the deposit	m²	2.10^6 - 700.10^6	---
V	Volume	m^3	$0{,}1.10^9$ - 100.10^9	1.10^{-4} - 0,1
t	Thickness of the deposit	m	10 - 200	---
α_1	Slope angle of the drop zone	-	10° - 45°	40°
α_2	Slope angle of the deposit zone	-	0° - 10°	0° - 6°

Table 34. Main variables for the modelling with their dimension and nature and model scale (- dimensionless; --- to be measure through modelling)

All these variables have already been used and introduced in the previous chapter (statistical analyses), except one for the thickness of the deposit. This variable has been introduced in order to complete deposit information. The thickness was measured at three different locations in the deposit (proximal, central and distal) to estimate the average thickness.

To allow an easier comparison between variables, six dimensionless ratios have been defined. The first of them (R_1) is known as the Heim coefficient; R_2 and R_3 were first introduced by Davies and McSaveney (1999) and relate the volume to the runout and the height of fall. These three first ratios can be directly compared with statistical results found previously (Tab.35).

Variable ratio	
R_1	$\frac{H}{L}$
R_2	$\frac{L}{V^{\frac{1}{3}}}$
R_3	$\frac{H}{V^{\frac{1}{3}}}$
R_4	$\frac{S^{\frac{1}{2}}}{V^{\frac{1}{3}}}$
R_5	$\frac{L.t}{V^{\frac{1}{2}}}$
R_6	$\frac{t}{H}$

Table 35. Dimensionless ratios

II.3. General methodology

This deals with sample preparation, the experimental procedure and the measurements made.

II.3.1. Preparation of the environment

Before each experiment, the ramp and the sandbox were carefully cleaned. Then the required features were fixed on the ramp and the entire structure cleaned again no make sure that no sand and plaster were left from any previous experiment. The experimental parameters (height of drop, slope angles of the drop zone and the environment) were checked before adding a known volume of sand to the system and starting the experiment. After every experiment, the ramp was cleaned and compressed air used to clean the sandbox. Sometimes a treatment spray was used to lubricate keep the opening surface of the sandbox.

II.3.2. Sample preparation

Once the modeling ramp was ready, the sample was prepared following a strict protocol.

The sand grading was checked by sieving using 100 and 600µm sieves. Then the correct amount of sand was weighed by using a balance with a precision of 10^{-2}g. Then plaster was added to the mix to add an extra 10% of the sand weight. The sample well mixed in order to avoid having two different layers in the sandbox.

II.3.3. Drop procedure

The drop was generated by using a box with a vertically opening door arranged to give consistent opening rate. This was done using a weight released from an electromagnet to cause the opening. The same box was used for every experiment, even with different volumes, however the shape of the sand was always the same.

During the collapse a camera recorded the formation of the deposit. This camera was located at the end of the sliding slope in order to cover the entire area.

II.3.4. Deposit studies

A strict study methodology was used for consistency. First the deposit was photographed with a scale next to it. These pictures were used to illustrate the result and to calculate the shape and surface of the deposit using *Photoshop* software. To avoid any distortion, one of the pictures was taken from vertically above the deposit perpendicular to the horizontal plane.

Then the length (Ln), width (W) and runout (R) of the deposit were measured with a ruler with a millimetric precision. The last parameter to be was done through destructive methods, (Fig.58). To measure the thickness of the deposit it was cut in half midway along its length. When possible, one half was removed, to allow measurement of the thickness with a scale at different position along the length (T1, T2, T3); otherwise the scale was pressed into the deposit and the thickness read on it.

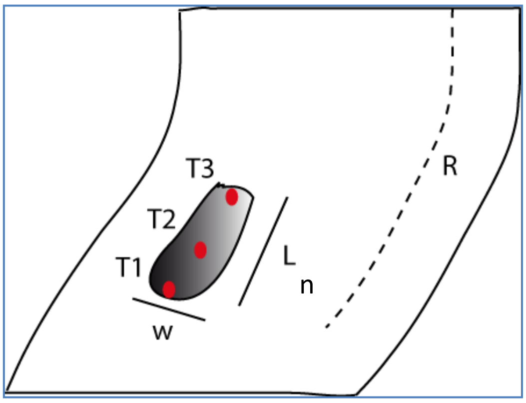


Figure 58. Illustration of measured parameters on the deposit

Each experiment was repeated twice to avoid incoherent result and to obtain an average of the measurements.

II.4. Results

The objective of this study is to quantify the effects of varying volume, fall height and the morphology of the environment on volcanic debris avalanches and their deposits. Each parameter has been analysed separately to observe its influence.

II.4.1. Impact of the volume

II.4.1.1. Principle and protocol

Three different volumes of sand were used (0.1L, 0.5L and 1L). In order to avoid any influence of the morphology of the environment, the mixture was released in an unconfined environment; the runout slope had no features. Three runs were done for each volume. These experiments were done with the sandbox fixed at 0.33m, at 0.52m and at 0.76m vertically above the lowest part of the runout slope.

II.4.1.2. Analyses

The results presented in the tables 36, 37 & 38 are the average of the three measurements for three runs of each parameter.

Parameters		Runout (cm)	Surface (cm^2)	Length (cm)	Width (cm)	Thickness max (cm)
Volume (L)	0,1	120,2	1588,93	49,33	27,67	0,7
	0,5	143,33	4366,07	75	49,33	1,2
	1	158,5	5301,67	94,33	53	1,87

Table 36. Influence of the volume on 5 different parameters of the deposit of an unconfined debris avalanche with a fall height of 0.76m

The smallest addition of volume to the initial volume has the greatest effect on the deposit. Of course, the proportional increase in volume is greatest for this smallest increase in absolute volume. Also, an increase of volume causes an increase of all deposit parameters.

Parameters		Runout (cm)	Surface (cm^2)	Length (cm)	Width (cm)	Thickness max (cm)
Volume (L)	0,1	64,5	790,26	32	27	0,9
	0,5	74,33	1387,5	43	41	1,87
	1	79	1835,68	50	49	2,47

Table 37. Influence of the volume on 5 different parameters of the deposit of an unconfined debris avalanche with a fall height of 0.33m

The same observations apply to fall heights of 0.52 m and 0.33 m. However the runout parameter increase is not proportional to volume increase for different drop heights; in fact, the increase is different from 0.1L to 1L for different height of drop (for H=0.33m, the runout increases by 22% and for H=1m, by 32%).

Parameters		Runout (cm)	Surface (cm^2)	Lenght (cm)	Width (cm)	Thickness max (cm)
Volume (L)	0,1	85,23	902,1	50	32	0,53
	0,5	110,33	2454,79	65	44	1,6
	1	119,5	3092,08	74	52	1,9

Table 38. Influence of the volume on 5 different parameters of the deposit of an unconfined debris avalanche with a fall height of 0.52m

II.4.1.3. Interpretation

An increase of volume means that more material is released from the source and in an unconfined environment this additional material tends to extend and spread more increasing the width and the length of the deposit. An increase of either the width or the length of the deposit increases the surface area of the deposit. As the increases of length and width are smaller than the increases of volume, the result is an increase of the thickness of the deposit. This has an impact on the runout which increases as well, however it is difficult to say if a small increase in volume causes a proportionally bigger increase in runout than a large increase in volume or if the increases proportional as there is not enough data (only three per height).

These results are similar to those found by Shea (2006) using similar apparatus and by Martinelli (2005) using different apparatus.

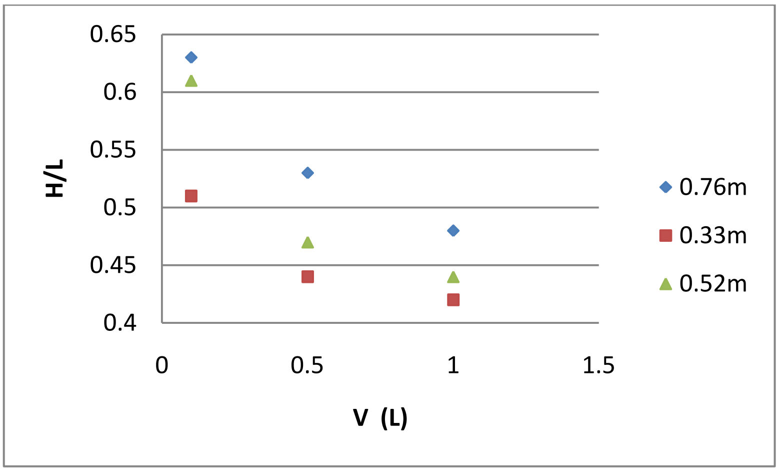


Figure 59. Comparison of H/L vs V with statistical and analogue data for unconfined DA

Figure 59 shows that, with all other variables held constant, an increase in volume causes an increase of the runout leading to a reduction of H/L. This observation has been made several times during other studies (e.g. Davies, 1982; Pollet, 2004; Martinelli, 2005), and by Shea (2006) using the same model. However, varying the drop height does affect the results, contrary to the conclusion of Davies (1982); but this effect decreases with increasing volume. In fact the variation of H/L with drop height for the same volume decreases by 50% when the volume increases by 90%. This suggests that the drop height has a greater influence on the results for small debris avalanches, but with large enough volume the volume has more influence than the drop height. The same conclusion was reached by Pollet (2004) when he showed that the drop height has a major impact on debris avalanche of a volume less than 1km^3; above this volume the drop height does not affect the runout.

II.4.1.4. Comparison with statistical analyses

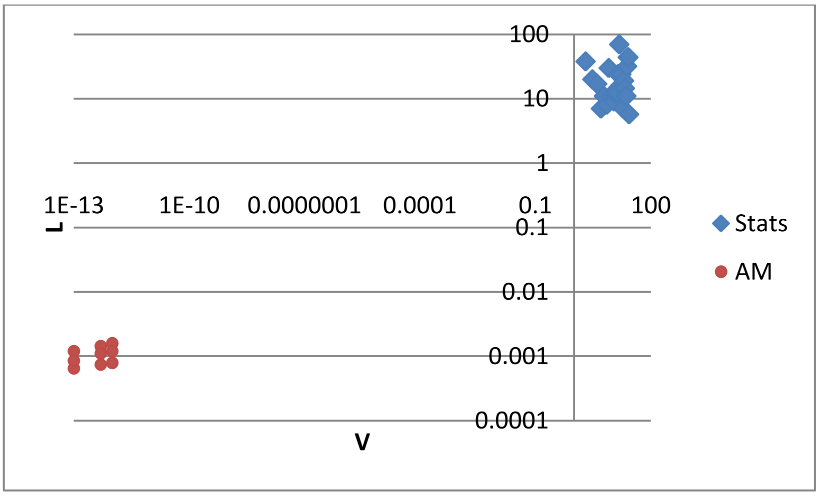


Figure 60. Comparison of L vs V for statistical and analogue data of unconfined DA

Figure 60 shows that, even though data are at the two extremes of scale, statistical and analogue data follow similar trends, however the statistical data are more scattered than the analogue ones due probably to greater variations in runout surface geometry.

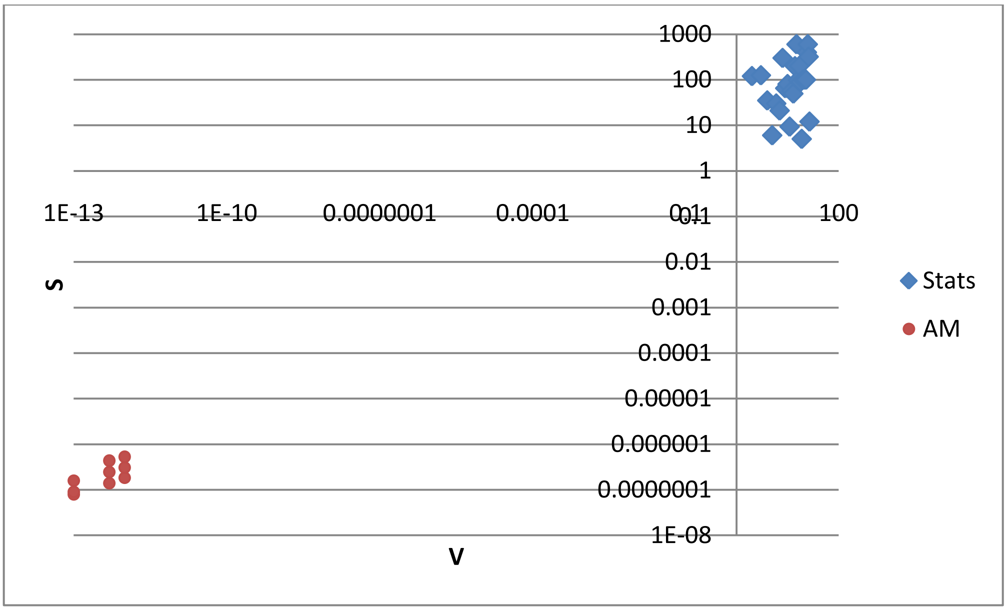


Figure 61. Comparison of S vs V for statistical and analogue data of unconfined DA

The same observation applies to the plot of volume against surface area (Fig. 61), even though the similarity between the two trends is less clear. It is perhaps the result of field error of the estimation of the surface, due to the different methods used to calculate the surface by each author and the quality of the preservation of the deposits. However these observations again suggest that statistical and analogue data have similar behaviours.

II.4.2. Impact of the height of drop

II.4.2.1. Principle and protocol

The aim of these experiments is to find out if the drop height has an influence on the debris avalanche and, if so, how important this influence is. The sandbox was fixed at three different heights above the lowest level of the runout surface (0.33m, 0.52m and 0.76m). As for the experiments with the volume, the mixture was released into an unconfined environment and each run was repeated three times. These experiments were carried out for volumes of 1, 0.5 and 0.1 L.

II.4.2.2. Analyses

The data presented are the average of the three runs for each parameter (Tables 39 & 40). The difference between the runouts for different drop heights has not been calculated since the slope profiles were different.

Parameters		Runout (cm)	Surface (cm^2)	Length (cm)	Width (cm)	Thickness max (cm)
Height (cm)	33	79	1874,25	50	49	2,47
	52	119,5	3092,08	74	52	1,9
	76	158,5	5301,67	94,33	53	1,87

Table 39. Influence of the drop height on 5 deposit parameters of a 1L unconfined debris avalanche

An increase in drop height causes an increase of the surface area, length and width of the deposit. The maximum thickness of the deposit decreases as the drop height increases.

Parameters		Runout (cm)	Surface (cm^2)	Length (cm)	Width (cm)	Thickness max (cm)
Height (cm)	33	74,33	1387,5	43	41	1,87
	52	110,33	2454,79	65	44	1,6
	76	143,33	4366,07	75	49,33	1,2

Table 40. Influence of the drop height on 5 deposit parameters of a 0.5 L unconfined debris avalanche

II.4.2.3. Interpretation

An increase of either the width or the length of the deposit causes an increase of the surface area of the deposit. An increase the length and the width of the deposit logically causes a reduction in thickness if volume remains constant. It is more difficult to analyse the runout; even if only the drop height is changed and all other things are kept the same, the runout will stop earlier for the smaller drop height (Fig.62). This is easily explained by the fact that for an identical slope profile, the lower level is reached in a shorter time for a smaller drop height than a bigger one which means that debris avalanche reaches the flatter zone earlier.

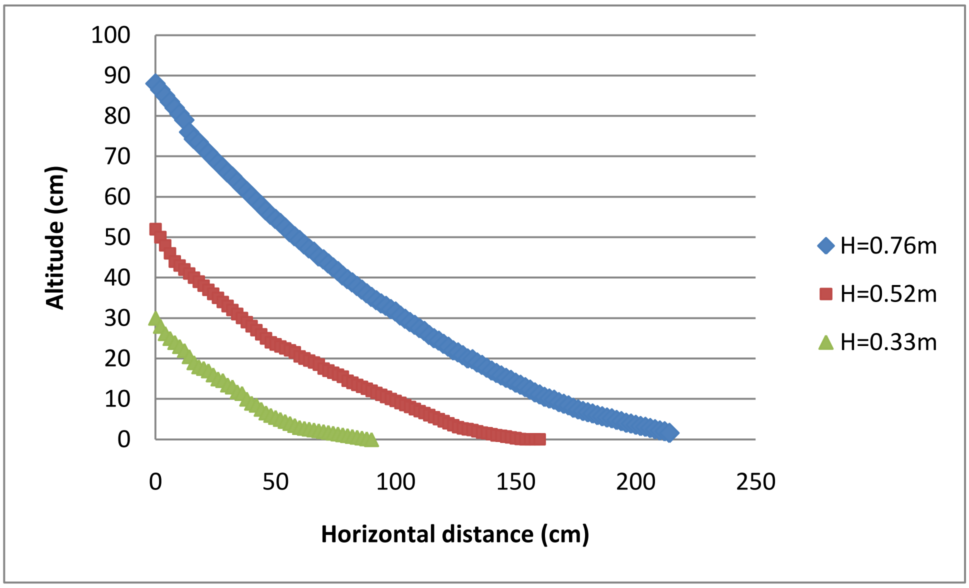


Figure 62. Representation of the slope profiles used for three different drop heights during the study

However, if the debris avalanche always stops before reaching the flatter zone then it is possible to compare the results by using height/runout ratio as the slope profile is the same for different drop heights. As all debris avalanches stopped before reaching the flatter zone during these experiments, this comparison is valid (Tab.41).

		V (L)		
		0,1	0,5	1
H (cm)	33	0,512	0,444	0,418
	52	0,610	0,471	0,435
	76	0,632	0,530	0,479
Maximum % difference		12%	8,60%	6.1%

Table 41. Experimental H/L ratios

Using these ratios, it is seen that for similar volumes, if the drop height is increased by 230% (33 cm to 76 cm) then the runout increases an average of 20% for all volumes. Thus the drop height has an influence on runout, but it is not large. This refines the conclusions of Hsü (1978) and Davies (1982) that the drop height does not affect the extent of the deposit. If the results are analysed with respect to the volume of the debris avalanche, it is possible to find the same trends as those pointed out in the previous section; the runout increase due to an increase of drop height is greater for smaller volumes than for larger volumes. This means that the smaller the volume, the bigger the impact of the drop height on the debris avalanche runout. This notion has been proposed previously (Pollet, 2004; Martinelli, 2005).

II.4.2.4. Comparison with statistical analyses

The second part of this study regarding the influence of the drop height was to test whether the analogue modelling experimental results correspond to the statistical database study. To do so, two plots are presented with logarithmic scales (Fig.63 & 64).

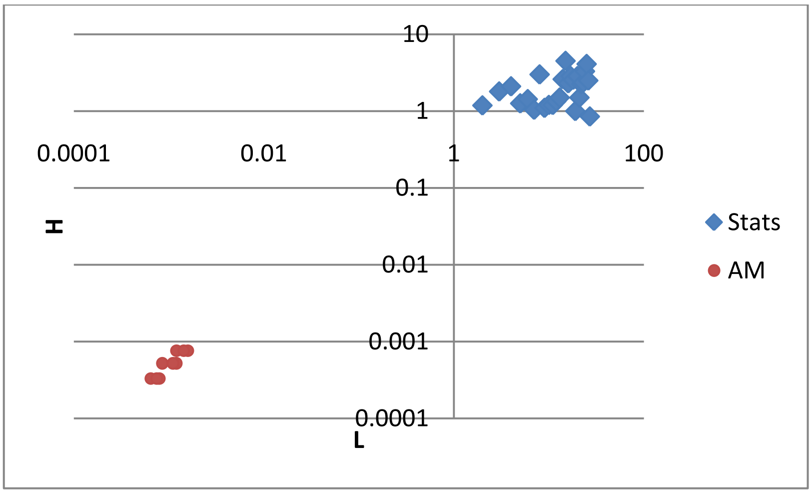


Figure 63. Comparison of H vs L between statistical and analogue data for unconfined DA

Figure 63 compares the two datasets in respect of the drop height and the runout. As expected the statistical data are more scattered than the analogue data, however both of them show a positive linear tend.

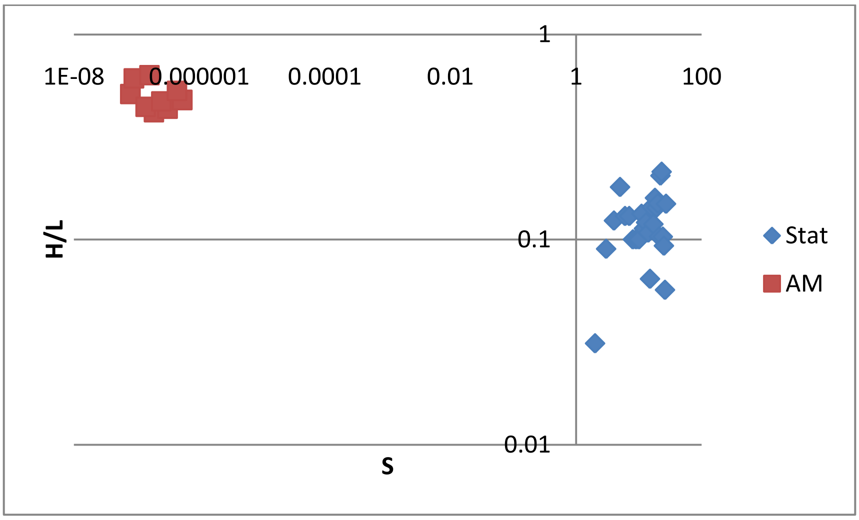


Figure 64. Comparison of H/L ratio vs S between statistical and analogue data for unconfined DA

Similarly, Fig. 64 compares the two datasets with respect to the H/L ratio and the surface area of the debris avalanche; again, statistical data are more scattered than analogue data. The data trend is the same in both datasets; both show that an increase of the surface area of the debris deposit has no effect on the H/L ratio.

II.4.3. Impact of the morphology of the environment

II.4.3.1. Principle and protocol

This final series of experiments was designed to observe the effect of different morphologies of the runout environment on debris avalanche deposits. Several features were introduced to the runout slope. To allow comparison between the tests, the same volume of material and the same fall height were used for each different environment.

II.4.3.2. Analyses

The results presented in the tables 42 to 45 are the average of the data for each three runs of each parameter.

Parameters		Runout (cm)	Surface (cm^2)	Lenght (cm)	Width (cm)	Thickness max (cm)
Environment	1 - Unconfined	158,5	5301,67	94,33	53	1,87
	2 - Semi-confined	160,00	2115,28	79,67	38,33	2
	3 - Confined (wide)	171,5	1452,56	84,8	25	2,5
	4 - Confined (narrow)	170,43	979,58	83,5	15	2,67

Table 42. Influence of the morphology of the environment on 5 different parameters of a debris avalanche for a volume of 1L and a height of drop of 0.76m.

The morphology of the environment represented in this table reflects a progressive increase of the lateral confinement of the debris avalanche runout path. The first observation is that runout and maximum thickness increase with the degree of confinement whereas surface, length and width all decrease. The degree of increase or decrease is more significant between an unconfined environment and a confined one (regardless of degree of confinement) than that between an unconfined and a semi-confined one. The difference between the wide and the narrow confined environments relative to an unconfined one is very small (less than 10%, except for the width of the deposit).

The thickness has a maximum increase of 42% from the unconfined to the very confined environment whereas the corresponding runout has the smallest increase with a maximum of 8.2%. This could be the result of experimental error. This is supported by the fact that for other drop heights, the thickness has a less important increase (a maximum of 10%).

Parameters		Runout (cm)	Surface (cm^2)	Length (cm)	Width (cm)	Thickness max (cm)
Environment	1 - Unconfined	119,5	3092,08	74	52	1,9
	3 - Confined (wide)	132,4	2135,15	86	25	2
	4 - Confined (narrow)	134	1565	93,67	15	2,1

Table 43. Influence of the morphology of the environment on 5 different parameters of a debris avalanche for a volume of 1L and a height of drop of 0.52m

The same outcomes are found with different drop heights. The only difference is a variation in the percentage results and the variation of the length. For drop heights of 0.52m and 0.33m, the length of the deposit increases with the degree of confinement; this is the opposite of what occurs for a drop height of 1m. However at 1m drop, the deposit length in a confined environment is greater than that in a semi-confined one. Only a volume of 1L and a fall height of 1m cause a decrease in the length compared to other fall heights. This suggests that the first observation is more likely due to experimental error, and that the length of the deposit does increase a little with the degree of confinement.

Parameters		Runout (cm)	Surface (cm^2)	Length (cm)	Width (cm)	Thickness max (cm)
Environment	1 - Unconfined	79	1835,68	50	49	2,4
	3 - Confined (wide)	87,57	1121	54	25	2,43
	4 - Confined (narrow)	94,47	970,5	62	15	2,53

Table 44. Influence of the morphology of the environment on 5 different parameters of a debris avalanche for a volume of 1L and a height of drop of 0.33m.

If, instead of a change in the degree of confinement, an obstacle is present on the pathway of the debris avalanche then the results are quite different.

Parameters		Runout (cm)	Surface (cm^2)	Length (cm)	Width (cm)	Thickness max (cm)
Environ ment	1 - Unconfined	158,5	5301,67	94,33	53	1,87
	5 - Triangle	148,27	2918,33	76,00	53,47	0,93
	6 - Barrier	144,83	2059	74,67	59,33	1

Table 45. Influence of the obstacles on 5 different parameters of a debris avalanche for a volume of 1L and a height of drop of 0.76m

Table 45 shows that an obstacle always causes a decrease of the runout, the surface area, the length and the thickness of the deposit. The only parameter that increases in the presence of an obstacle is the width of the deposit.

II.4.3.3. Interpretation

As expected, if the degree of confinement is more important, then the width of the deposit is less important. In addition to the reduction of the width, the length of the deposit decreases with decreasing degree of confinement which logically causes a reduction of the surface area of the deposit. The thickness obviously increases. This increase of thickness had been pointed out as well by Martinelli (2005) even though she used a different model but tested the impact of different degrees of confinement of the environment on debris avalanches.

If the degree of confinement is modified, so is the runout following the same trend (if the confinement increases, the runout increases as well; Fig.65). However the modification of the runout is not extreme as the runout increases by 15% from an unconfined environment to a narrow path of 15cm.

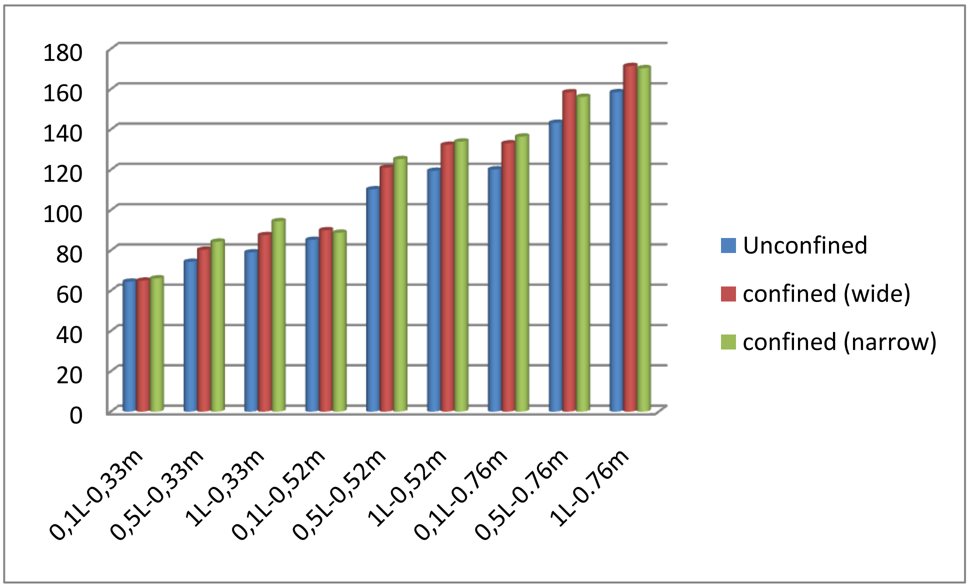


Figure 65. Runout related to the degree of confinement

Shea (2006) concluded that the degree of confinement does not seem to influence the runout because the difference in the runout parameter was extremely small. The degree of confinement does affect the avalanche runout but it is not the main factor determining the runout. However, the morphology of the environment is not only represented by confinement.

Obstacles in the runout path cause results opposite to those of confinement; they cause a decrease of both the length and the thickness of the deposit (Fig.66). This is because a certain volume of debris is stopped by the obstacle, which means a smaller volume of debris takes part in the final runout. An obstacle increases the width of the deposit, because in going around the obstacle the debris avalanche is forced to widen itself.

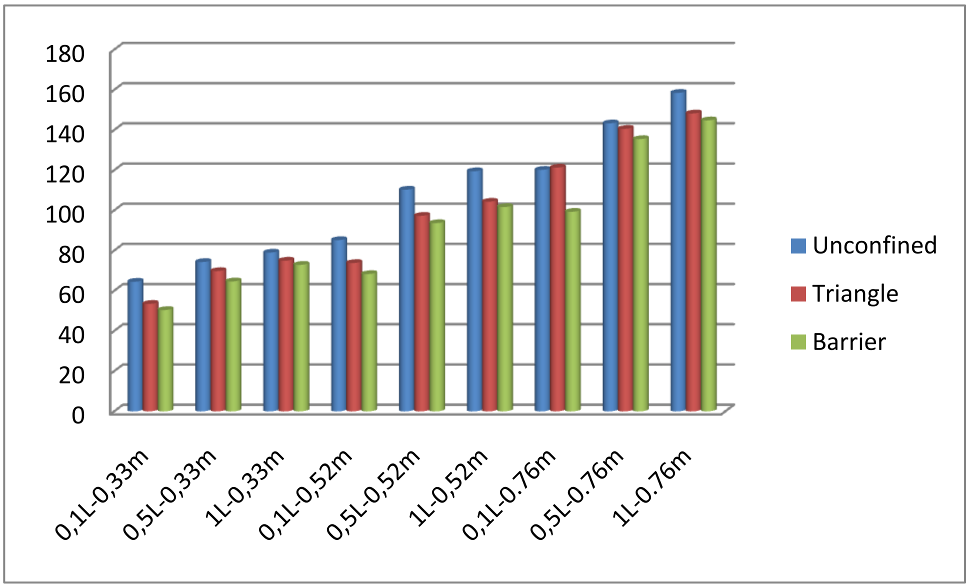


Figure 66. Impact on the runout of the presence of obstacles on the avalanche pathway

It can be notice that if the volume is not modified, a decrease of the fall height or the presence of an obstacle on the avalanche pathway causes a decrease of the runout. This supports the hypothesis of Pollet (2004) that any impact of the debris avalanche with a topographic feature consumes energy, and the bigger the feature relative to the size of the debris avalanche, the bigger the energy consumption. This is illustrated by the fact that the triangular obstacle decreases the runout less that the barrier obstacle, because the avalanche is only deflected by the point of the triangle, whereas it is stopped and has to change its direction when it encounters the barrier. Further, the runout of smaller debris avalanches is affected more that of than larger debris avalanches. In addition, larger debris avalanches can in part go over the obstacle whereas smaller debris avalanches have to go around it (in the experiments, only debris avalanches of 1L were able to go over the obstacles). This idea was introduced by Pollet (2004), when he pointed out that the behaviour of the debris avalanche and the loss of energy vary according to the ratio between the height of the obstacle and the thickness of the debris avalanche encountering the obstacle. A smaller obstacle is easily overtopped by the debris avalanche which loses little energy (example A; Fig. 67), a medium obstacle can be partly overtopped and partly bypassed by the debris avalanche which thus loses more energy (example B) and a large obstacle can either be bypassed by the debris avalanche (if it is not too wide) or will stop it the debris avalanche (example C).

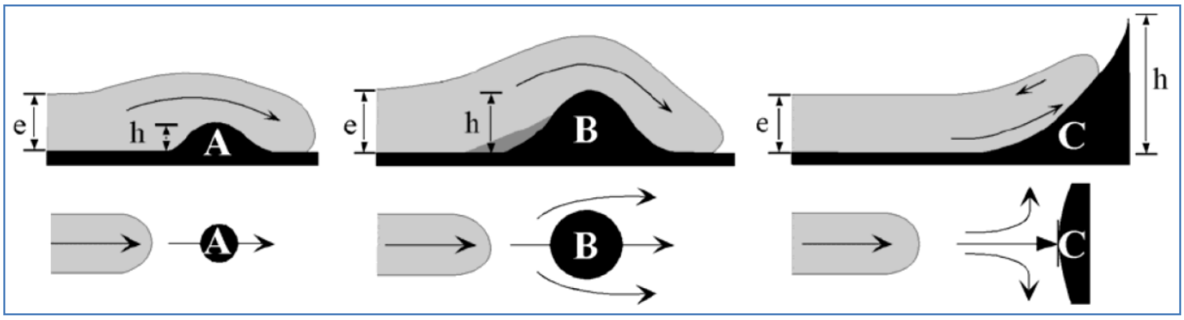


Figure 67. Illustration of debris avalanche behaviour affected by obstacles of different thickness (from Pollet, 2004)

Another interesting aspect is the shape of the deposit in response to obstacles (Fig.68). The experiments show that for unconfined or confined environments the deposit tends to have an elongate shape. On an unconfined slope the deposit is fan-shaped because the debris avalanche naturally spreads itself laterally. If an obstacle (triangular or barrier) is present on the runout path the deposit will have a lobate shape because the debris avalanche has to bypass the obstacle, causing a free-from-deposit area downstream of the obstacle. Even if the avalanche is large enough to go over the obstacle, the amount of material able to go over the obstacle is not enough to cover the entire surface from the obstacle to the end of the avalanche runout.

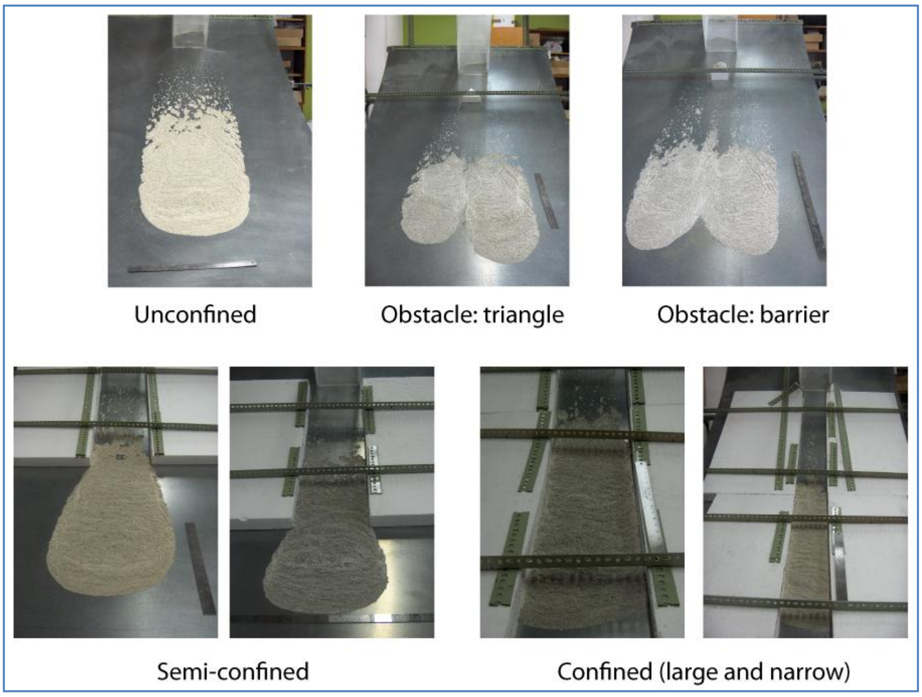


Figure 68. Illustration of the shape of the deposit regarding the morphology of the environment

All these observations show that the environment has an impact on the debris avalanche deposit even though it is not the most significant factor affecting the runout, but it seems to be the main factor affecting the deposit geometrical characteristics (width, shape and thickness).

II.4.3.4. Comparison with statistical analyses

The second aim is to check if the analogue modelling results match the statistical ones found using the field deposit database regarding the morphology of the environment. However, a few elements need to be clarified. First of all, the morphology of the environment prior to a prehistoric debris avalanche is not always known and may have been inferred from the deposit shape. Secondly, in the database only the degree of confinement has been considered, so this is the only parameter compared between the statistical study and the analogue modelling (Fig.69).

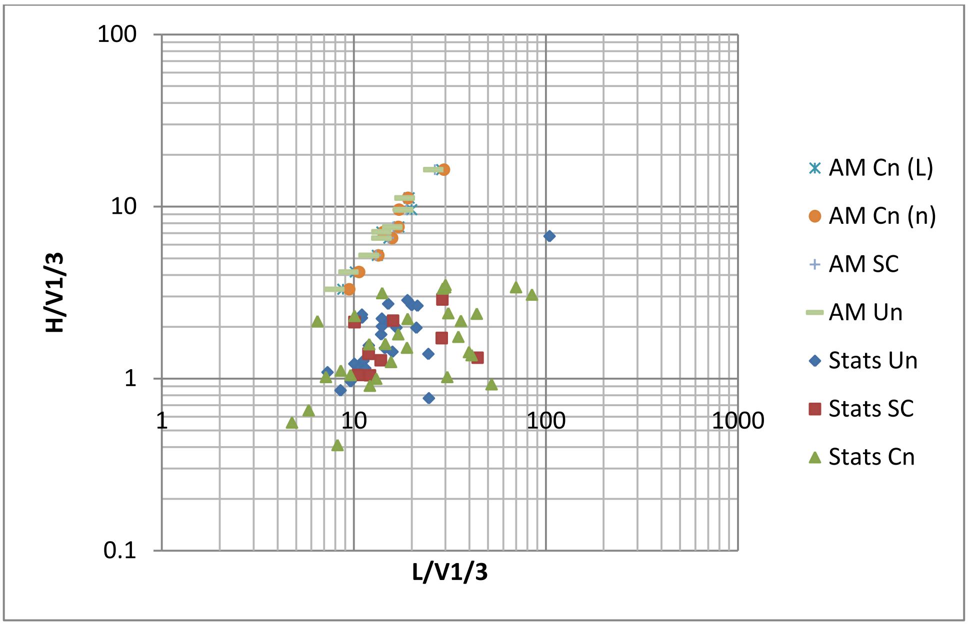


Figure 69. Comparison of $H/V^{1/3}$ & $L/V^{1/3}$ ratio between statistical and analogue data (Un = unconfined, Sc = semi-confined, Cn = confined, S = statistical & A = analogue)

Different ratios have been used to compare these two types of data in order to be able to use a logarithmic scale. It is interesting to note that although statistical data are more scattered than analogue ones, both follow a linear trend. However as found by Shea (2006) these two linear tends are not parallel, there is still a difference between real cases and analogue modelling ones. As for the impact of the morphology of the environment, both data (statistical and analogue) point out that for an equal $H/V^{1/3}$ confined debris avalanches are closer to $L/V^{1/3}$ ratio. A similar repartition trend seems to occur regarding the degree of confinement.

II.5. Conclusions

After having analysed the results obtained from every parameter, it is interesting to draw a general conclusion and link these different parameters.

II.5.1. Influence of the volume and the height

These effects of the volume and the drop height have been studied since the Mt St Helens eruption in 1980. Two main theories exist, the first that the volume and the drop height have a strong influence on the debris avalanche characteristics (Straub, 2004), whereas the second presumes that the volume has a great influence but the drop height has no influence on the runout (Hsü, 1932; Davies, 1982).

This study showed that the volume has an influence on the debris avalanche as an increase of the volume of material involved (at the beginning of the drop) implies an increase of all parameters studied (runout, surface, length, width and thickness of the deposit). An increase of the height of drop increases all these parameters except the thickness of the deposit, which decreases. However, the volume has a much greater influence on the debris avalanche characteristics than the drop height, especially on the runout. In addition, the influence of drop height on runout is significant only with small avalanche volumes; the bigger the avalanche, the less effect the drop of height on runout.

II.5.2. Influence of the morphology of the environment

The morphology of the environment is believed to have an impact on debris avalanche deposit characteristics (Siebert, 1984; Pollet, 2004), especially regarding the relationship between the morphology of the environment and the morphology of the debris avalanche.

Herein the effect of two morphological parameters was studied; degree of confinement and the presence of obstacles. An increase of the degree of confinement causes an increase of the runout, length and thickness and a reduction of the width and the surface area. However an obstacle on the debris avalanche runout path causes an increase of the width and a reduction of the runout, surface, length and thickness. The behaviour of the debris avalanche depends on the size of the obstacle relative to the size of the avalanche; a smaller obstacle is easily overtopped and/or bypassed.

The morphology of the environment is an important parameter in understanding debris avalanche geometrical characteristics, especially the shape of the deposit.

II.5.3. Implication for volcanic debris avalanches

This study highlights the influence of the initial volume of material involved, the drop height and the morphology of the environment on debris avalanche deposit characteristics, especially geometrical characteristics. The volume has a greater influence on the debris avalanche than the drop height. However when the areas at risk are to be determined, the morphology of the environment has to be studied and used as it is responsible for the debris avalanche deposit geometrical characteristics such as the shape. Apparently the morphology of the environment has not only an impact on the deposit geometrical characteristics; recent studies have suggested that topography might control the style of caldera subsidence, and in turn the volume of any resultant debris avalanche (Walter & Troll, 2001).

To complement the analogue and statistical modelling, a corresponding numerical modelling exercise has been carried out, which will be now introduced and explained.

III. Numerical modelling

Numerical modelling requires certain knowledge in programming. This modelling can be done by creating new software where everything can be done with the same software (programming, modifications, and simulation representation). Or it is possible to use known software and to create only a specific application or code that will be used.

III.1. Software

Volcflow is a computer code that runs with a programming language software called *MATLAB* (MATrix LABoratory). It needs at least the 2007b version of *MATLAB* to work.

III.1.1. Presentation

The simulating code has been created by Karim Kelfoun from the French research unit 'Laboratoire Magmas et Volcans' in 2004-2005 in C informatics language (Fig.70). The aim of this code is to simulate volcanic flows (pyroclastic flow, debris avalanche, lava flow) however sedimentation and other flows can also be represented such as mud flow or tsunami.

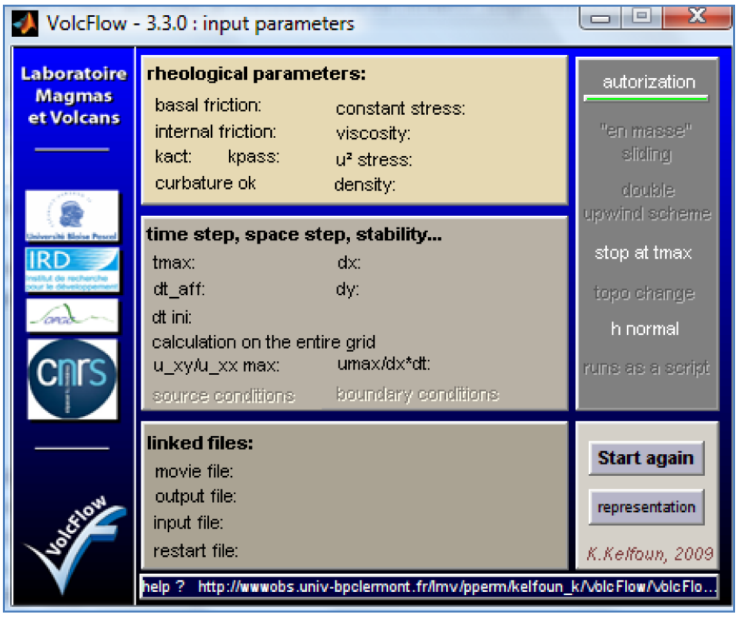


Figure 70. *Volcflow* application window

This code is based on a depth-average approximation, where equations are solved using a shock-capturing numerical method based on a double upwind Eulerian scheme. However this code is based on the assumption that the bulk of the avalanche slid on a thin basal layer (which is commonly assumed for granular flow) and that any excess pore fluid pressure is negligible (Kelfoun and Druitt, 2005). This depth-average approximation is represented by a topography-linked coordinate system with x and y as horizontal points (parallel to the local ground surface) and h as a vertical one. After each time increment new thickness, velocity, x and y component are calculated. Various rheologies can be used (frictional, Bingham, viscous) or can be created by modification of the initial code.

This code can be used for several purposes such as the determination of the rheological behaviour of the flow, the visualization of the surface deformation or the area affected by the flow. This last use is the most interesting one for this study as geometrical results can be compared with those from analogue modelling and statistics.

III.1.2. Artefact

This code, that can be very useful in drawing volcanic hazard maps and determining areas at risk, is still quite new and depends on the understanding of flows. As knowledge of flows improves some improvements and verifications of the code will need to be done.

The code is currently being improved in order to be used under other applications than the *Microsoft Windows* one.

The main problem is the fact that the modelling may be unrealistic. It is very important to be critical regarding the results and the code used. This can be quite problematic when a complex rheological behaviour is modelled as it is not entirely understood and based on suppositions.

III.2. Lab modelling results comparison

This section of the chapter explains why a numerical modelling has been used for this study and any differences or similarities with the analogue modelling.

III.2.1. Aim

As explained before a numerical modelling is the result of a human creation and is based on actual knowledge and suppositions. This code, which is working very well for the Socompa debris avalanche in Chile, needed to be tested against lab data to check if it is good enough to represent field-scale debris avalanches. This previous verification is necessary as the code will be used later for the case study on the Taranaki.

To do so, some analogue modelling experiments carried out earlier have been reproduced using *Volcflow*. However some changes in the code needed to be done for accurate modelling and these are explained in the following section.

III.2.2. Principle

In order to use *Volcflow* with the laboratory experiments, some modification in the code were required to use the same initial parameters. First of all, the environment of the drop (slope) needed to be created (Fig.71). To make it as similar as possible to the analogue slope, coordinates of the slope (x, y, and z) have been measured every 2 centimetres to reproduce the original slope. Once the environment was created, initial parameters such as the volume and its initial shape, the features on the slope, and the material density were added to the code. The material was characterised as Mohr-Coulomb behaviour with a basal angle of 25° and an isotropic internal pressure.

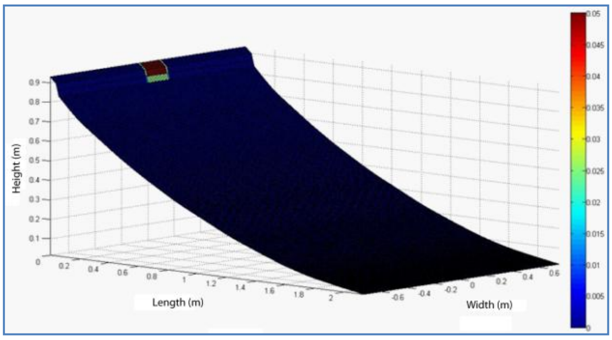


Figure 71. Reproduction of the analogue modelling slope with the numerical code

A series of drops have been run to reproduce experiments for different environments with an avalanche of a volume of 1L.

III.2.3. Numerical and analogue experiments

The aim of this section is to compare the results obtained from the numerical modelling to those measured when using the analogue modelling.

III.2.3.1. Methodology

To be able to compare results from the two different modelling, the same data are required and to ensure that a methodology has been used (Fig.72). Data can be known either by scale reading or by selected a plot and accessing its characteristics. The runout was the easiest data to collect as it can be known simply by reading the scale (horizontal runout). However the width is not directly given and an additional calculation is needed (addition of the maximum and the minimum values). The shape and the thickness of the deposit are directly read from the graphic.

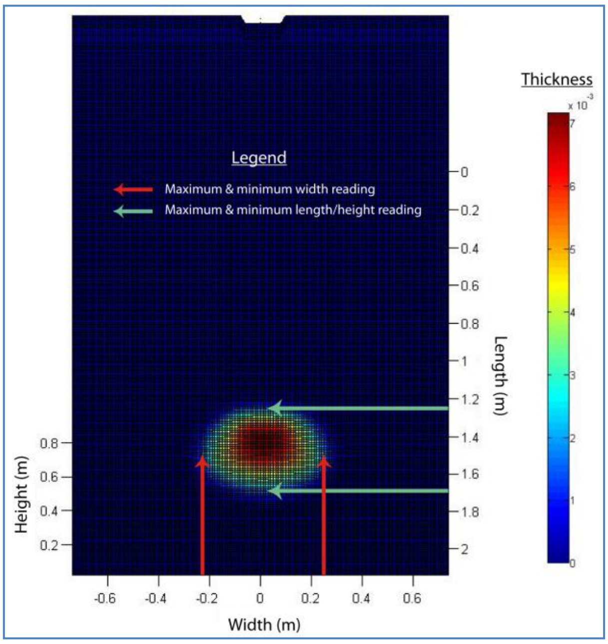


Figure 72. Data reading with Volcflow

The length of the deposit cannot be obtained by reading or with a simple calculation. An approximation needs to be done during the calculation. It was decided to simplify the slope surface to the hypotenuse of a rectangle triangle where the maximum and minimum length and the maximum and minimum height are known. Using Pythagoras' theorem the triangle hypotenuse was calculated: AC = $\sqrt[2]{(AB)^2 + (BC)^2}$ where AC is the deposit length (Fig.73).

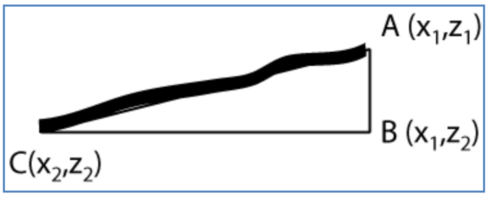


Figure 73. Calculation of the length

The length found by this method is approximate however it can be used to check the importance of the difference between the two models.

III.2.3.2. Results

The comparison has been done for results obtained on a 40° angle of the slope and a volume of debris avalanche of 1L. The horizontal runout has been called maximal distance (max. distance) in order to avoid any confusion with the resultant runout (horizontal and vertical).

III.2.3.2.1. Unconfined environment

The unconfined environment code is the most basic of all the codes used for this study as no features had to be added to the slope.

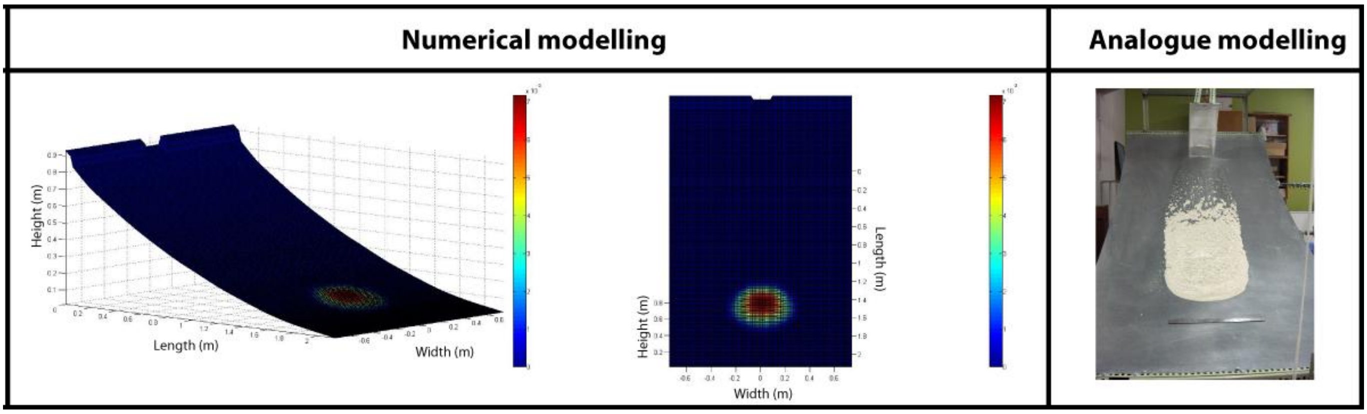


Figure 74. Unconfined debris avalanche deposit from the numerical and analogue modelling

Both deposits are elongate however the deposit from the analogue modelling tends to extend farther up the slope than the numerical one (Fig.74). This observation can be confirmed by the fact that the approximate length calculated 22% less than that measured the laboratory. Two parameters of the deposit are quite similar in both models: width (2.17%) and maximal distance (5.92%) of the deposit (Tab.46).

	Analogue	Numerical
Max. distance (m)	1.59	1.69
Width (cm)	45	46
Length (cm)	94	73
Shape	Elongate	Elongate

Table 46. Unconfined debris avalanche deposits results comparison between the numerical and the analogue modelling

The result from both models are quite similar, the only major difference is the location of the upslope end of the deposit. This difference affects the length and the general shape of the deposit which give differences between the two modelling results.

III.2.3.2.2. Semi-confined environment

The semi-confined environment code is the based on the unconfined environment code; the only difference is the two features added to half of the slope to create two walls on both sides (Fig.75).

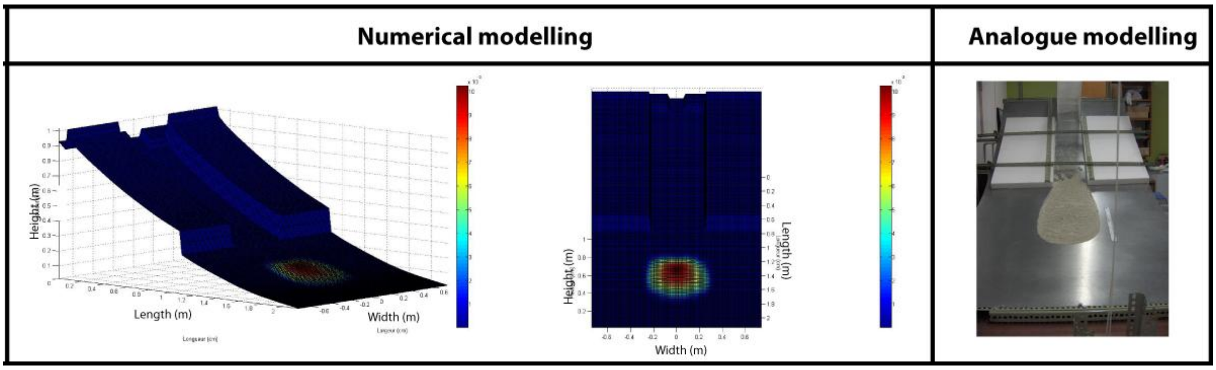


Figure 75. Semi-confined debris avalanche deposit from the numerical and analogue modelling

The deposit is elongate however the analogue model deposit extends farther up the slope than the numerical one causing a difference in length of 6% (Tab.47). However the analogue modelling deposit slowly reaches its elongate shape whereas the numerical modelling deposit is almost directly elongate. The main difference is the fact that there is a difference of 22% in the widths of the deposits; the numerical deposit is wider than the analogue one. The maximal distance reached by the deposit is quite similar for both modelling since the difference is equal to 5.88%.

	Analogue	Numerical
Max. distance (m)	1.60	1.70
Width (cm)	38	49
Length (cm)	79	74
Shape	Elongate	Elongate

Table 47. Semi-confined debris avalanche deposits results comparison between the numerical and the analogue modelling

The result from both models are quite similar, the only major difference in a semi-confined environment is the width of the deposit which has a small impact on the shape as well.

III.2.3.2.3. Wide confined environment

The code used for the wide confined environment is very similar to the one used for a semi-confined environment. The only difference is that the walls have been changed to be longer so that the debris avalanche will be confined on its entire pathway (Fig.76).

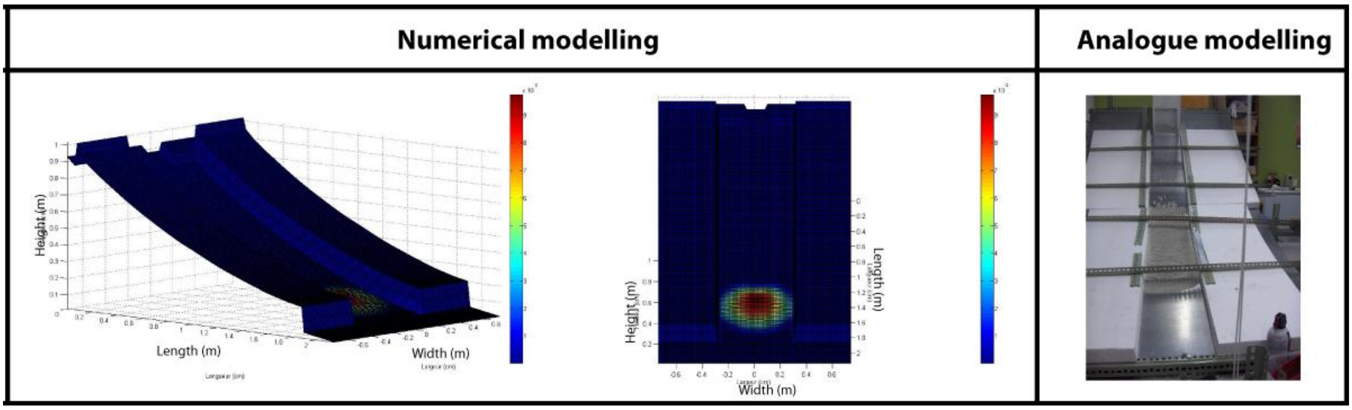


Figure 76. Large confined debris avalanche deposit from the numerical and analogue modelling

The results between the two modelling are quite similar since the differences in maximal distance, the width and the length are less than 1.5% (Tab.48). The shape is similar, however not entirely the same. The analogue modelling deposit again seems to be longer than the numerical modelling deposit.

	Analogue	Numerical
Max. distance (m)	1.72	1.73
Width (cm)	25	25
Length (cm)	84	83
Shape	Elongate	Elongate

Table 48. Large confined debris avalanche deposits results comparison between the numerical and the analogue modelling

The only main difference between the two modelling is in the general shape of the deposit. It is still an elongate shape but shorter for the numerical deposit than the analogue one.

III.2.3.2.4. Narrow confined environment

The only difference between the code used for the large confined environment and the narrow confined environment is the width between the two walls.

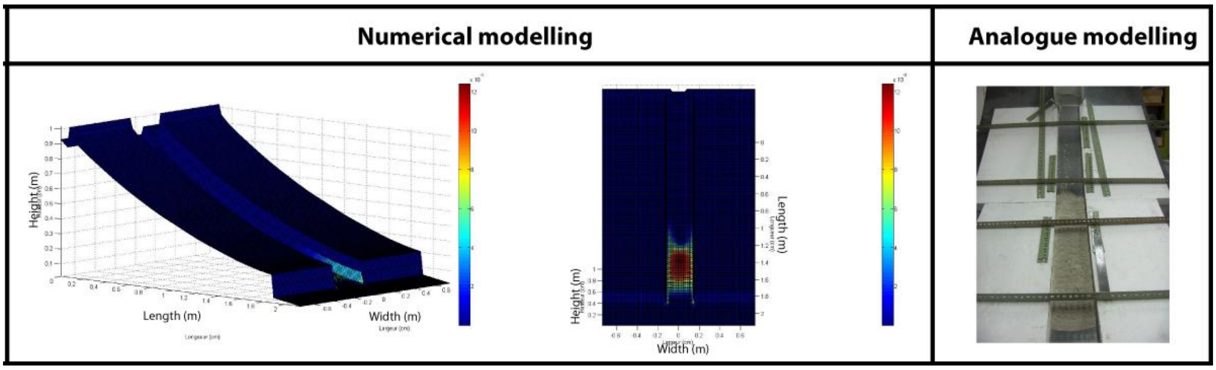


Figure 77. Narrow confined debris avalanche deposit from the numerical and analogue modelling

Numerical and analogue modelling deposit are very similar for this environment (Fig.77). The difference between the maximal distance and the width of the deposits is less than 2%. The shapes are quite similar and the only significant difference is for the length of the deposit - less than 4% (Tab.49).

	Analogue	Numerical
Max. distance (m)	1.71	1.74
Width (cm)	15	15
Length (cm)	84	87
Shape	Elongate	Elongate

Table 49. Narrow confined debris avalanche deposits results comparison between the numerical and the analogue modelling

The results for a narrow confined environment are very similar between numerical and analogue modelling.

III.2.3.2.5. Barrier on the slope

The code has been modified to create a barrier of 10cm width and 5cm long on the slope at 30cm from the opening system, to match the experiment done in the laboratory.

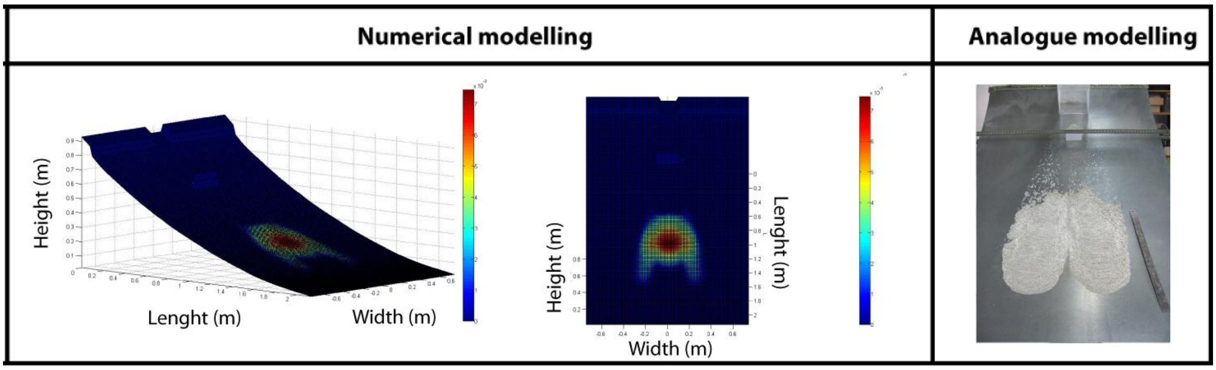


Figure 78. Debris avalanche deposit with a barrier on the slope from the numerical and analogue modelling

Both deposits have a lobate shape, however this shape is more accentuated on the analogue modelling (Fig.78). The maximal distance reached by the deposit and the width are quite similar (difference less than 7%; Tab.50).

	Analogue	Numerical
Max. distance (m)	1.50	1.45
Width (cm)	55	59
Length (cm)	57	75
Shape	Lobate	Lobate

Table 50. Debris avalanche deposit with a barrier on the slope from the numerical and analogue modelling results

The biggest difference between these two modelling experiments is the length. However a difference is expected for this parameter as it is calculated by estimation.

III.2.3.3. Conclusion

The similarities between the numerical and analogue modelling are quite important since most of the time the differences represent a percentage less than 6% (Fig.51).

	Max. distance	Length	Width
Unconfined	< 3%	22%	< 3%
Semi-confined	< 3%	6%	22%
Large confined	< 1,5%	< 1,5%	< 1,5%
Narrow confined	< 1%	< 4%	< 1%
Barrier	3%	24%	6.8%

Table 51. Differences percentage between numerical and analogue modelling

Some of the differences between the two models can be explained by the fact that the conditions of the environment are more likely to alter in the laboratory (temperature, humidity ...) which can have an impact on the results. Another explanation can be the fact that the numerical modelling is based on the actual knowledge of the characteristics of the material used for the experiments. This knowledge might evolve with time to be more precise and even closer to the reality.

Another aspect is the fact that the numerical modelling is more precise than the analogue one - very small particles can be identified by the software that the eye may not be able to see on the slope.

It seems that the more modified the environment, the more similar the results between the numerical and analogue modelling. In general, the numerical modelling tends to give an extra 10cm for the width and the distance of the deposit; these extra centimetres can be used as a security margin (margin of error) when developing any scenario of debris avalanches on a volcano.

IV. Conclusions

IV.1. Laboratory modelling

The analogue modelling pointed out several results. First of all, the drop of height has more impact on smaller debris avalanche than larger ones. Then relations between H, V and L are the same even if different morphologies of the environment are used: the height of drop has a more important influence on small debris avalanche.

It does not mean that the morphology of the environment has no influence whatsoever on debris avalanche. It does however depend on the volume of the debris avalanche. For the same morphology of the environment, larger debris avalanches are less affected than smaller ones. This impact of the morphology of the environment is more on geometrical characteristics of the deposit (shape, surface, with, length, thickness) than the runout. However, an increase of the degree of confinement increases the runout slightly whereas the presence of an obstacle on the pathway decreases the runout slightly.

The comparison with the statistical database study highlighted the fact that the processes involved for debris avalanche are similar in nature and at the laboratory, as the results apart from using different scales have similar tends.

IV.2. Numerical modelling

As seen during this study, numerical modelling with *Volcflow* code was successfully used to reproduce experiments run in the laboratory. The differences pointed out between laboratory experiments and the numerical modelling are the result of laboratory error (in the measurements for example) and the parameters used as inputs in the numerical modelling. In fact four main categories of parameters are needed to run the numerical modelling and a good knowledge of those is important to obtain the best and most realistic simulation. These parameters are the following:

- The topography of the environment,
- Some characteristics of the substratum (nature, angle of friction),
- The collapse scar characteristics (height, depth, width, length),
- The debris avalanche characteristics (volume, friction angle, density, behaviour),

Numerical modelling is a powerful tool which can simulate and represent volcanic events such as debris avalanches. However it has to be used with care and the results should also be verified as an error can be easily made. It can be a good complement to studies especially those about debris avalanche geometrical characteristics and the areas affected by them.

As general tends have been pointed out through the statistical and modelling studies, these trends will be tested using *Volcflow* code to carry out a case study (following chapter).

Chapter 4. Case study

To illustrate some aspects of the present work, the case study is a simulation of a debris avalanche on the north flank of the Taranaki volcano, North Island, New Zealand. However before describing the simulation, the geology and topography of the area has been outlined. The initial characteristics of the region have been studied as well in order to appreciate the threat to the neighbourhood (population, economy and infrastructures) a debris avalanche represents.

I. General description of the area

Mount Taranaki (formerly Mount Egmont) is volumetrically the largest andesitic stratovolcano of New Zealand, located in the centre of Taranaki in the western part of North Island (Alloway et al, 2005). This 2518m-high volcano has two official names; it was for many centuries called Taranaki by Maori, and when Captain Cook arrived, he decided to name it Mount Egmont after the first lord of the Admiralty John Perceval, second Earl of Egmont.

I.1. Geological description

To understand the presence of debris avalanches in this area, the general geology and the volcanology are described.

I.1.1. Geology of the area

The Taranaki Peninsula is an onshore component of the Taranaki Basin (Fig.79), a sedimentary back-arc basin along the west coast of the North Island made up of two major structural blocks: the western Platform and the Taranaki graben (Pilaar and Wakefield, 1978). These two blocks are separated by the Cape Egmont Fault Zone, a series of steep en-echelon normal and reverse faults (King and Thrasher, 1996). The tectonically active graben is limited at its eastern boundary by the Taranaki Fault, which is an east-dipping reverse fault, and the Mania Fault Zone, series of steep en-echelon east dipping reverse faults (Voggenreiter, 1993).

This regional depression, which is an expression of New Zealand's predominantly transcurrent fault system, has had a complex tectonic history related to deformations associated with the evolving Pacific-Australian plate boundary (King and Thrasher, 1992). It is a set between the Patea-Tongaporutu High (a basement high called Eastern Province) and the Western Platform (an area of the continental shelf) that has been subsiding gently since the late Cretaceous (around 80 million years ago) without major disruption beneath a shallow sea (Neall, 1983; Haskell and Palmer, 1984). This sequence of sediments which overlie Paleozoic and early Mesozoic formations (120-240 million years old) can reach a thickness of at least 6 km (McBeath, 1977).

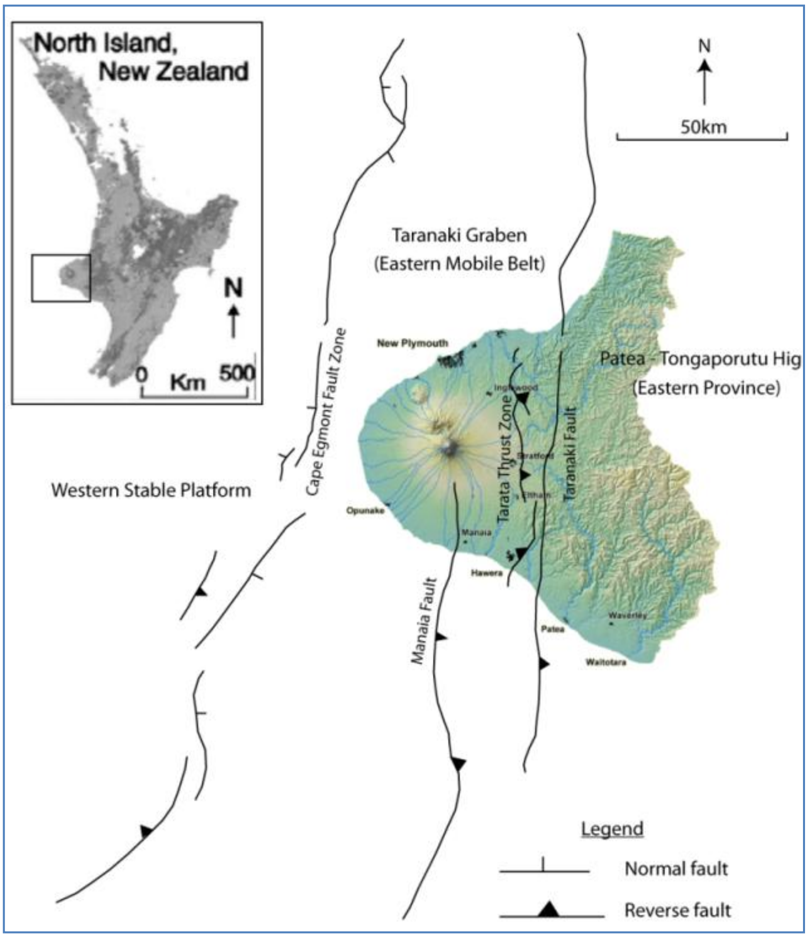


Figure 79. Main structural elements in the Taranaki Basin (modified from Pilaar and Wakefield, 1978; Muir et al, 2000)

I.1.2. Volcanic history

Volcanic activity of the Taranaki area is distributed over the time between the early Pleistocene (around 2 million years ago) until the present (Fig.80). It is not the result of one volcanic edifice but a sequence of remnant edifices (Price et al, 1999); four major edifices have been built since the early Pleistocene. These andesitic cones are aligned and follow a NNW-SSE trend along an apparent major linear fracture in the earth's crust referred to as the Taranaki Volcanic Succession or Taranaki Volcanic Lineament. It is bounded by the north-east trending Cook-Turi lineament to the north and the Taranaki Fault to the South (Neall et al, 1986; Price et al, 1999).

The volcanic rocks are mainly andesites rich in potassium. Some dacites (central parts of Kaitake and Pouakai), basaltic andesites and high-alumina basalts (Fantham's Peak) can also be found (Neall, 1983; Price et al, 1992; Price et al, 1999). Lavas became progressively richer in potassium with time and the most recent lavas have the highest silica content (Stewart et al, 1996; Price et al, 1999). The most abundant phenocryst phase in rocks is plagioclase, followed by clinopyroxene, amphibole and titanomagnetite. Orthopyroxene and olivine are less common (Stewart et al, 2006).

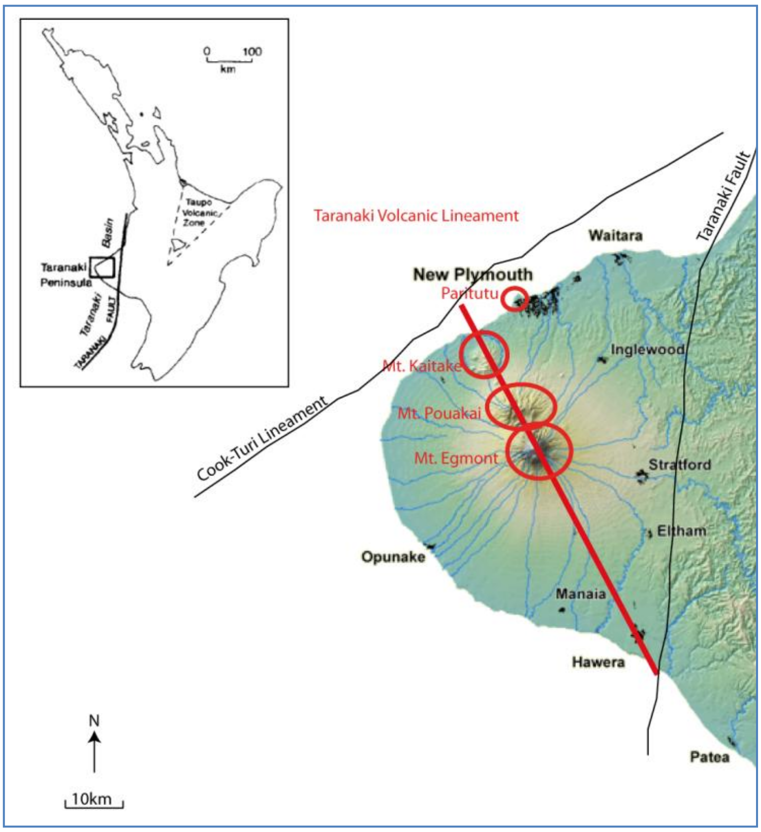


Figure 80. Illustration of the Taranaki Volcanic Lineament (modified from Crozier and Pillans, 1991)

This activity progressing southwards along this fracture with time has lead to the creation of:

- Paritutu and Sugar Loaves at around 1.75Ma (Price et al, 1999); these are not exactly on the lineament axis,
- Kaitake about 15km south west of New Plymouth around 0.57Ma (Neall, 1973),
- Pouakai around 0.25Ma, 10km south-east of Kaitake, covering an area about half to two-thirds that covered by present-day Taranaki at its base (Neall, 1983),
- Finally Taranaki, less than 0.12Ma; the last known eruption was in 1750 (Alloway et al, 1995). The volcano can be subdivided into two sections: an upper and lower section. The upper section consists of lava flows from Mount Taranaki and Fanthams Peak (a southern flank parasitic vent that has been active since at least 7000 years ago). The lower section is an extensive ring plain around the volcano mainly composed of debris flows and lahar deposits due to cone collapses (Stewart et al, 2006).

These collapses created volcanic landscape features in the ring plain that were described and later identified as volcanic debris avalanche deposits (Neall et al, 1986; Procter et al, 2009).

I.1.3. Debris avalanches of the Taranaki Volcanic Lineament

Several debris avalanche deposits have been recognized in the ring plain of the volcanoes and at least 8 formations have been mapped (Fig.81). These deposits are characterized by the block facies (usually called axial a), the mixed facies (called axial b) and the marginal facies in which the proportion of inter-clast matrix is dominant (more than 90%) and the surface physiography is without mounds or hills (Stewart et al, 2006). These deposits are separated into two broad stratigraphic units: 'Old Ring Plain' for the deposits emplaced before 24 ka and 'Young Ring Plain' for those emplaced between 24 and 8 Ka (Price et al, 1999).

These deposits affect an area of about 250km² and have individual volumes of at least 3.5km^3. The topography of the environment affected some of the avalanches as some of them have been bifurcated (Okawa formation) or channelized (Ngaere formation).

Two debris avalanches occurred in the north of the lineament and affected the area of New Plymount: the Maitahi and the Motunui formations. The Maitahi formation consists of debris flow and avalanche deposits derived from Pouakai volcano whereas the origin of the Motunui formation is unclear; if may have originated from a youthful ancestral Taranaki volcano or an actively degrading Pouakai volcano (Alloway et al, 2005; Stewart et al, 2006).

The Taranaki Volcanic Lineament edifices have repetitively collapsed over their history, and it has been calculated using the method of Stirling and Wilson that collapse of a volume less than 0.15km^3 occurs about every 2000 years and a volume greater than 7.5km^3 about every 21,000 years (Alloway et al, 2005).

A debris avalanche can be the result of a magmatic activity, however the initiation can also be triggered by non-volcanic activity. This region is seismically active, which means that earthquakes occur in the area and can affect the volcanoes. Another element characteristic of this region is the amount of precipitation; between 8000 and 2400 mm of rainfall occur every year which result in a discharge of 28 million cubic meters per week for all the rivers within a 12km radius (Palmer et al, 1991). So a lot of water is present in the volcanic pile which can be the primary component in the event of a collapse (chemical transformation by creation of clay more particularly allophane, or physical changes by modification of the pore-water pressure) but not enough to saturate the debris (at least at the beginning). As the cover bed is composed of clay-rich element (allophone and ferrihydrite) this potentially enhances the mobility of the flow (Vallance and Scott, 1997).

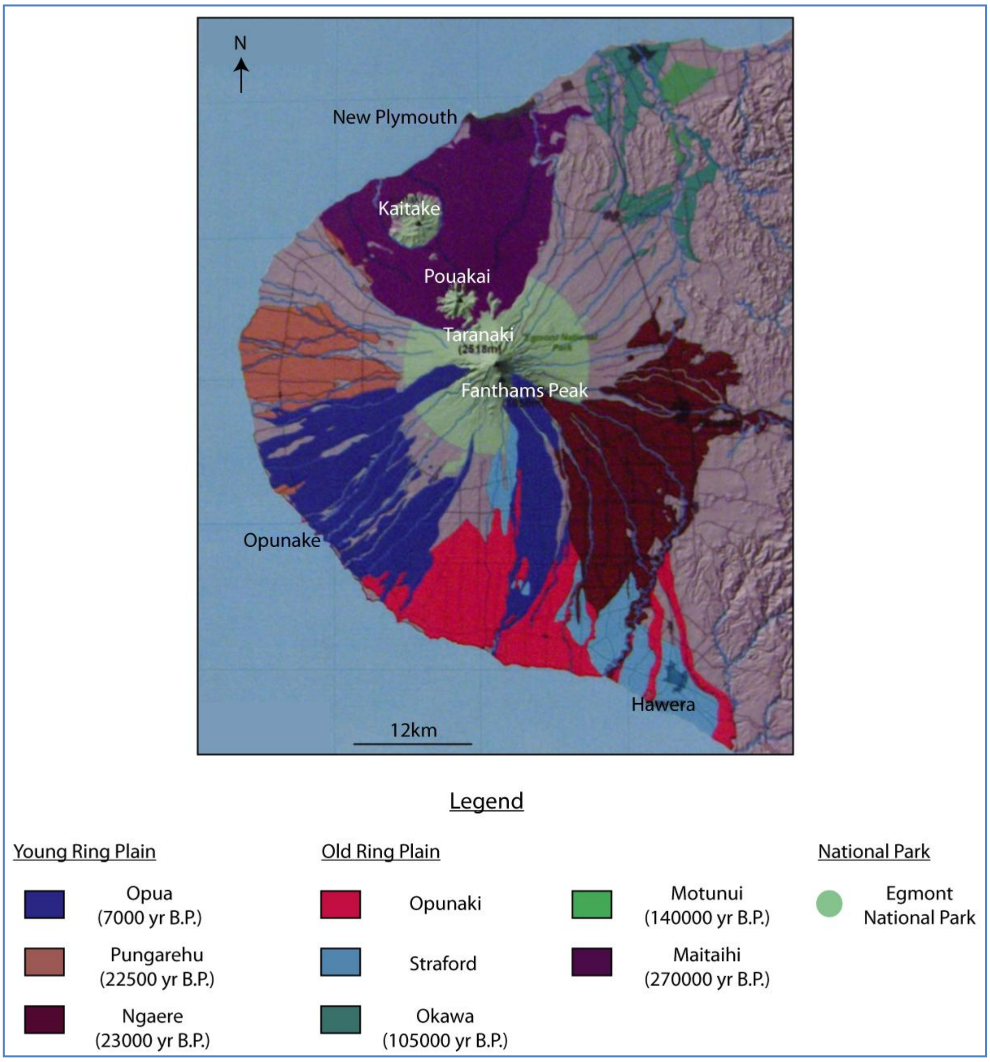


Figure 81. Distribution of onshore debris avalanches of the Taranaki Volcanic Lineament

(modified from Stewart et al, 2006)

Why focus this study only on the north of this ring plain? This question will be answered in the following part by introducing this area to understand its importance.

I.2. Importance of the area

The importance of a region can be categorized as: demographic, economic and real estate.

I.2.1. Demographic aspect

The Taranaki region has been inhabited for several centuries now. It started with Maoris at about 800 A.D. and was followed by European settlers in the early 1840s. This area is divided into three districts (New Plymouth, Stratford and South Taranaki) and has about 104000 inhabitants (104127 in 2006) with a continuing concentration of the population in the New Plymouth District (Fig.82). This particular district contained not less than 66% of the population of this region in 2006, which corresponds to a total of 68724 persons (Taranaki Regional Council, 2009).

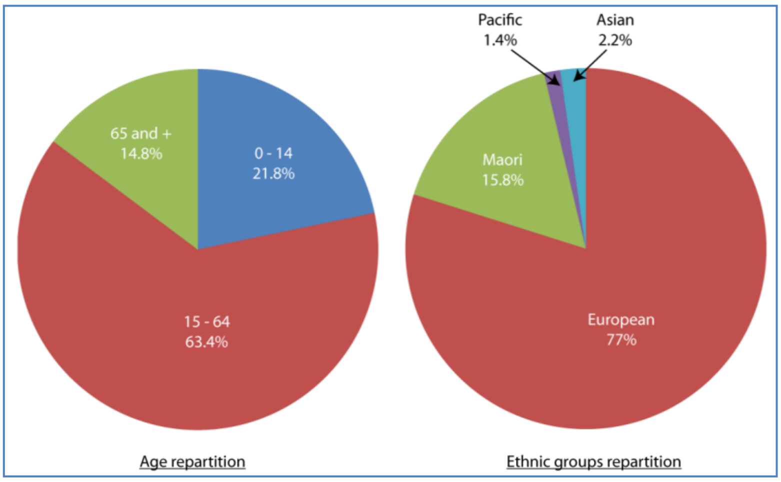


Figure 82. Characteristics of the population of New Plymouth District (Based on the Taranaki region age and ethnic groups' average)

This population is composed of 227,700 children younger than 15 and 14,411 adults older than 65. This means that 36.6% of the population of the New Plymouth District rely on others and cannot always drive; this is important as these people will be the most vulnerable in case of emergency as they may have some physical disabilities and/or lack of knowledge regarding the volcano. 77% of this population is of European ethnicity, which means that if they have not lived in this region for long, they are not very familiar with volcanic hazards; also, English might not be their first language which can be problematic in an emergency. The same problem arises for 3744 more persons as 1.4% are from Pacific Islands and 2.2% from Asia. However 15.8% are from a Maori iwi which means that they have a close relation to the volcano as it is considered to be almost a relative; there are cultural stories of people who experienced activities of the volcano.

I.2.2. Economic importance

The economy of the region is based on seven main areas involving natural and physical resources. *Agriculture and forestry* provide work for 16% of the population and contribute 20% of the region economy (NZ$850 million). This activity, mainly dominated by dairy farming, is particularly located in the ring plain. It is complemented by *pig and poultry farming*, concentrated in New Plymouth District. These two economic fields represent more than 1.3 million animals and 2821 farms. The region, through its *horticulture and cropping* activity, is also self-sufficient in most crops and some fruits are exported. The *manufacturing* and the *retail and service* industries are the largest employer fields (18% and 15% of full-time workers), and the *tourism and event* industry is growing with 274,738 visitors and an increasingly important role.

However the region is best-known for the sediments of the Taranaki Basin that contain New Zealand's primary *oil and gas* reserves (Fig.83). The region produces all the oil and gas of the country as it is the only commercial hydrocarbon-producing area. Extensive exploration has been done is the area, including numerous drill holes (Stewart et al, 2006); however this area is still under-exploited and potential for very large oil and gas reserves in deep water further off the Taranaki coast is high (an estimated reserves of 55 million barrels of oil remain and an estimated 147 million barrel in known non-producing fields).

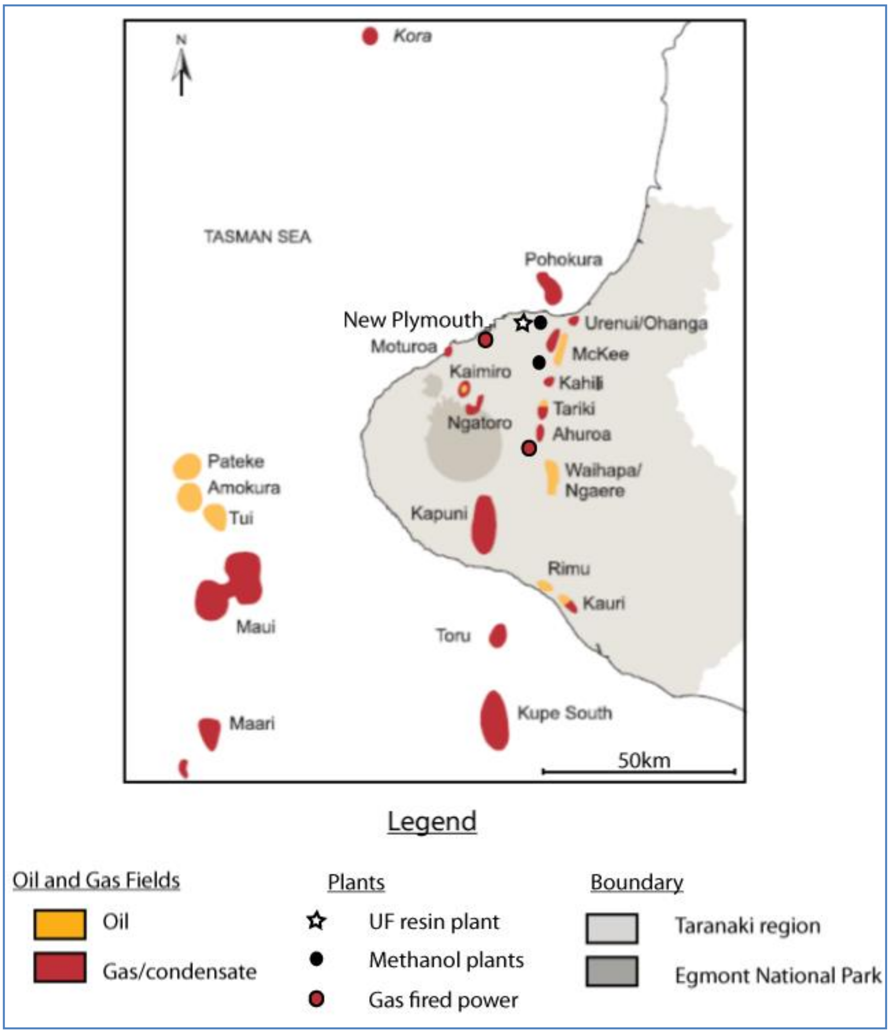


Figure 83. Distribution of the main oil and gas fields (modified from Taranaki regional council, 2009)

Even though the entire region provides oil and gas, New Plymouth District is particularly important as the only two methanol plants and the only UF resin plant are in this district. Half of the treatment plants and gas-fired power are installed at the main harbour of New Plymouth. This activity represents 1.8% of the region's fulltime employment but creates 3000 jobs from derived industries. It contributes 17% of the region economy (NZ$741 million) but if other industries impacted by it are included it represents NZ$1 billion (Taranaki Regional Council, 2009).

I.2.3. Infrastructure

The economy of the region is supported by its infrastructure (Fig.84). This infrastructure can be purely for economic activity (manufacturing sites, plants, pipelines) but it is also for vital (hospital, fire brigade, electricity network, school, and transport) and for luxury purposes (airport, harbor, mall, and stadium). The infrastructure is important as it has a direct impact on peoples' lives and most of them are concentrated in New Plymouth District.

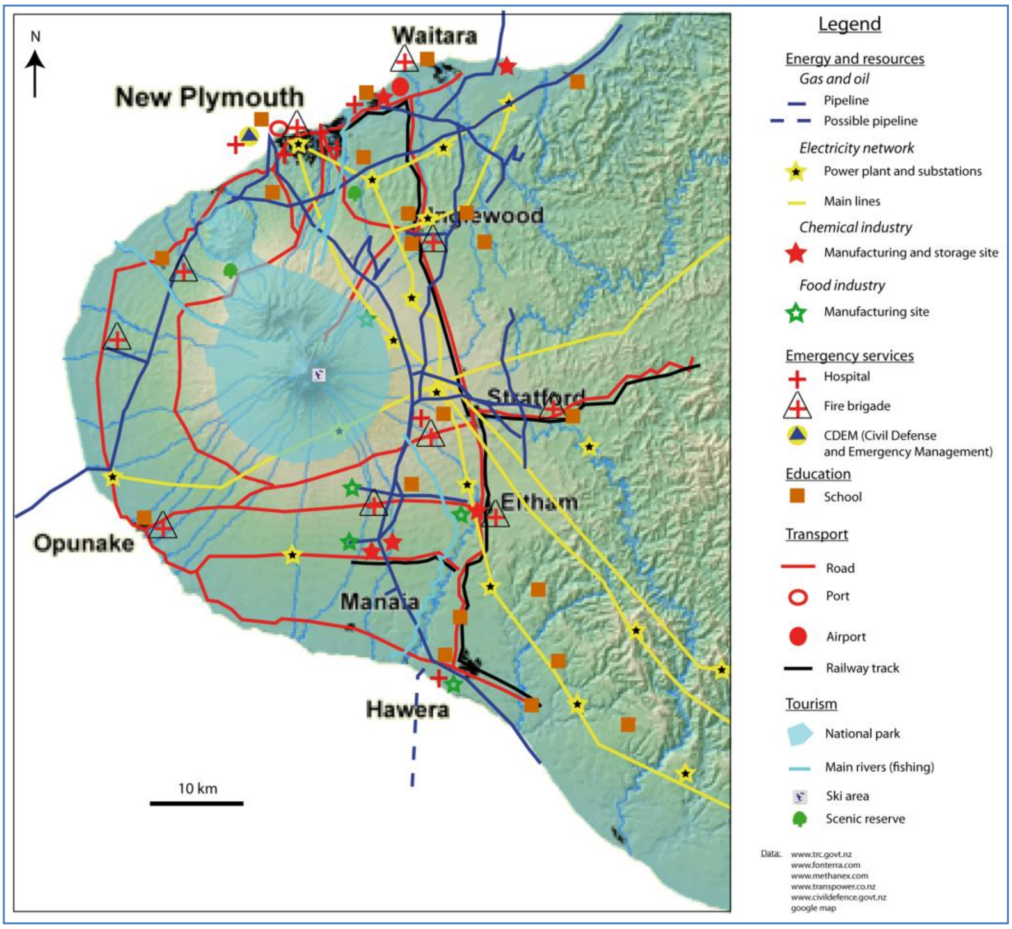


Figure 84. Distribution of the main infrastructure of the Taranaki region (modified from Pouget, 2008)

The infrastructure is rapidly developing; in the past 5 years the number of building consents increased to 1635 with a value of NZ$193100000 in 2007 for the New Plymouth District. New areas are developing such as the Waiwhakaiho valley for retailing, the Bell Block for industrial use and the periphery of New Plymouth for residential properties.

However infrastructure can be also associated with historic heritage which represents important elements of the district (Fig.85). It can be of architectural, cultural, historic, scientific or technological nature. For the district of New Plymouth, 805 heritage buildings have been listed (including house, church, tower, memorial and commercial building) which represent 60% of the region's heritage buildings and 727 archaeological sites, the equivalent of 41% of the region's sites.

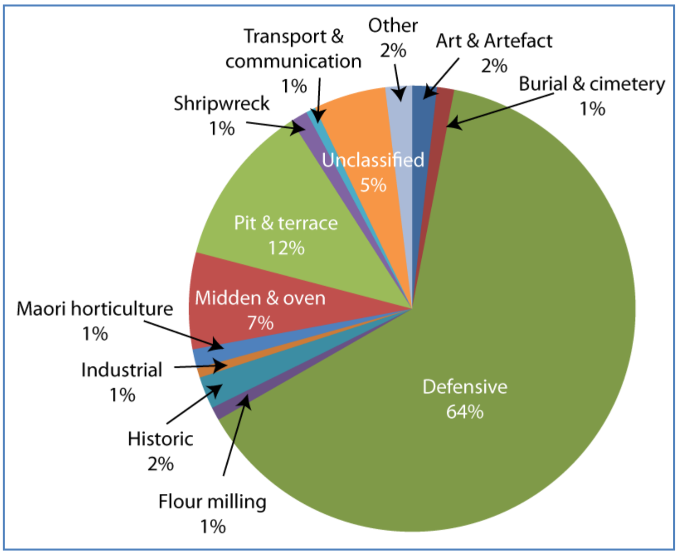


Figure 85. Historic heritage of New Plymouth District

In case of a major volcanic event affecting this district, the impact on the region will be very important not only from an economic and industrial point of view, but also affecting the demography and the ecology (flora, fauna and marine life).

II. Simulation of debris avalanche on the north flank of Taranaki volcano

The aim is to use *VolcFlow* to test several scenarios of debris avalanches on the north flank of Mount Taranaki. The scenarios differ by the volume involved in each simulation. The objective is to see how the region can be affected by a debris avalanche.

II.1. Principle

II.1.1. Code settings

The first task was to represent the topography of the north flank of the volcano and the region of New Plymouth (Fig.86). To do so a Digital Elevation Model (DEM) of the Taranaki region was used with a contour interval of 50m . To this DEM the underwater elevation data had to be added to cover the topography of the entire area studied. However instead of using these marine data, it was decided to represent the sea by a flat area with a neutral altitude (0m) rather than negative elevations. This choice was motivated by three main raisons. First of all the fact that it was more difficult to see where the coastline was, that makes the location of towns more difficult. Secondly, the version of *VolcFlow* used for this study does not model tsunami. In the case of a debris avalanche reaching the sea, the results will be accurate as the behavior will be as if the flow was still subaerial. Thirdly, on a more practical aspect, the more detailed and larger the area is, the longer the simulation takes to be completed.

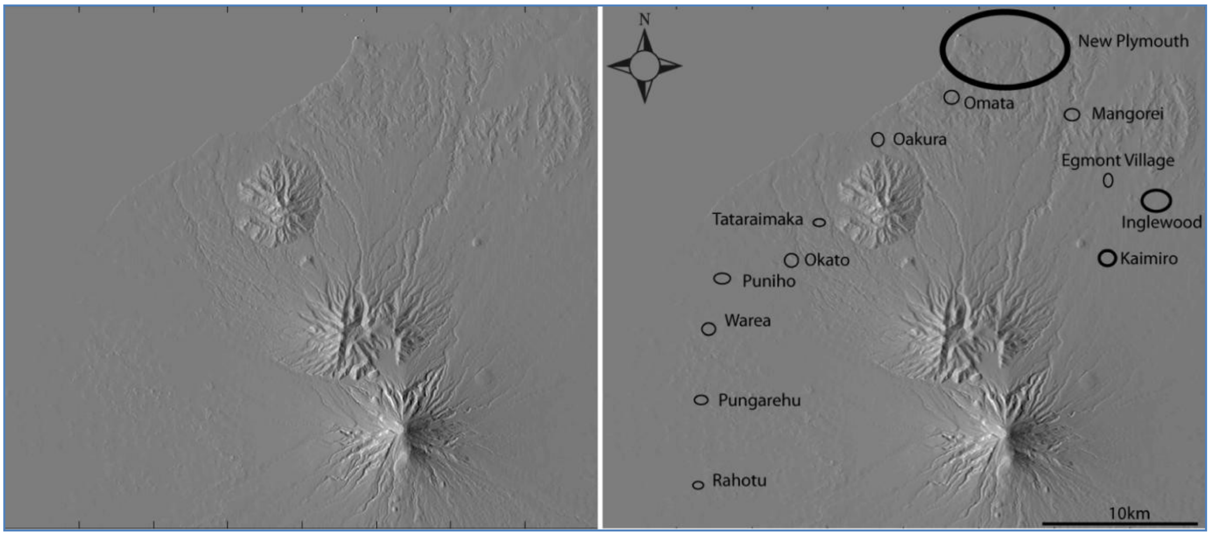


Figure 86. Topography used for the simulations

Once the topography was integrated into the code, the collapse scar characteristics had to be created. It had been decided that the scar should be on the north flank of the volcano, include the summit of the volcano and have a bowl shape. The shape was created using an equation composed of a parabolic curve on the Y axis and an elliptical curve on the X axis.

Then specific parameters for a debris avalanche were set such as the flow behavior. The basal resistance used for these simulations is the same as that used for the extremely successful Socompa simulation: 50kPa (Kelfoun and Druitt, 2005).

II.1.2. Methodology

The first step was to determine the volume of the avalanche for the simulation; to do so the equation of the collapse scar was modified. However only the lowest and highest points of the collapse scar were changed (Fig.87), the general equation used was the same and the width of the collapse scar was not modified. 4 different volumes have been tested: 0.77, 2.19, 3.67, 4.78 km^3. A volume of less than 1 km^3 was simulated in order to see how a small debris avalanche might behave as a small event is more likely to happen than a large event. Two debris avalanches were modelled with volumes greater than 3.5 km^3 as most of the debris mapped avalanches are at least of this volume. One of the objectives was to simulate the largest debris avalanche possible on this flank of the volcano; however it had to be done without involving the collapse of the entire volcano. This is why a maximum volume of 4.78 km^3 was used.

Once the code was ready to be run, the second step was to illustrate the collapse scar from different angles before the debris avalanche begins. Then the simulation was run until it was complete, before illustrating of the deposit from different angles.

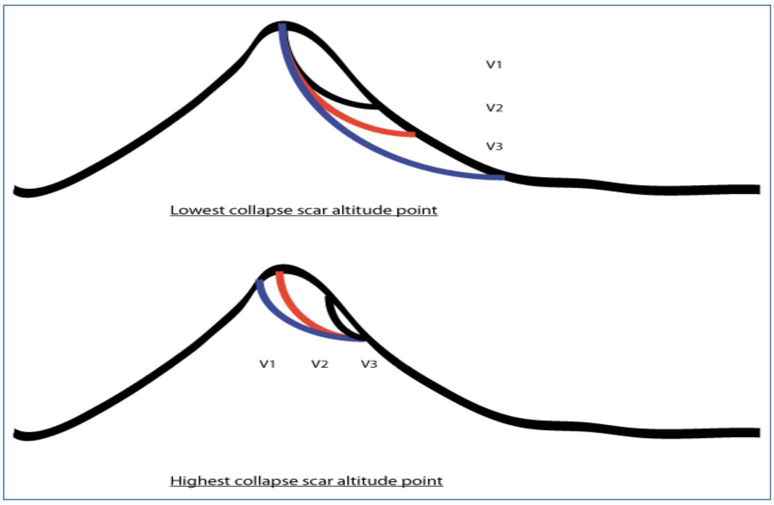


Figure 87. Example of different volume by modifying the collapse scar

II.2. *Volcflow* simulations

II.2.1. Results

To allow visualisation of the results, a table with different parameters for each simulation was created (Tab.52).

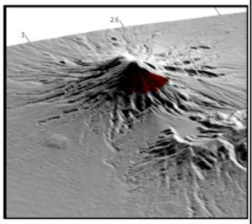
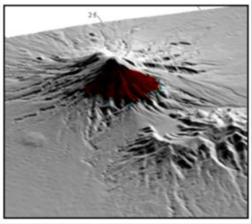
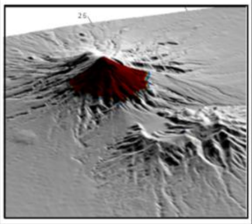
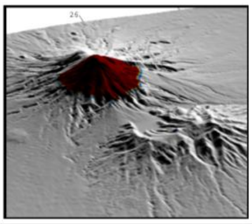
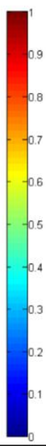
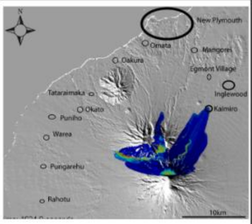
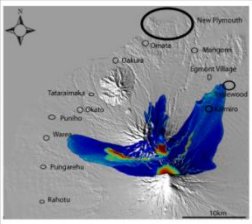
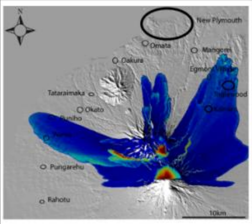
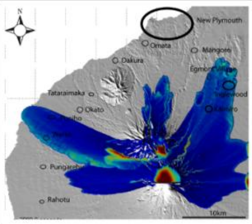
Volume (km^3)	0.77	2.19	3.67	4.78	
Collapse scar					Thickness 
Deposit					

Table 52. Results of the Taranaki debris avalanches simulations

The simulations showed that a debris avalanche on the north flank of the volcano affects three main directions: north, east and west. The smallest volume tends to give a deposit concentrated in between the volcano and the barrier and reaches a maximum distance of 12 km in the town of Kaimiro in the direction of Inglewood. Increasing from 0.77 km^3 to 2.19 km^3 increases the runout dramatically - it reaches a maximum distance of 17 km, and the deposit affects a part of Inglewood. The runout reaches 24 and 25km for volumes of 3.67 and 4.78 km^3 respectively.

II.2.2. Interpretations

The simulations were carried out in order to see the effect of topography on the avalanche. However several limitations of these simulations must be pointed out before interpretation of the results. The debris avalanche deposit is dependent on the initial shape of the collapse scar and its location on the flank. These simulations were run without knowledge of actual weaknesses in the summit and the collapse area. First of all, this means that it is quite unlikely that the next north-flank debris avalanche collapse scar will be exactly like those created for these simulations. Secondly, if the collapse scar is slightly more on the east or on the west, the proportion of the avalanche going in one of the three main direction is different (the flow is more important on the west if the collapse scar is slightly more on the west of the north flank). Another limit is the fact that the region has a very intense network of rivers.

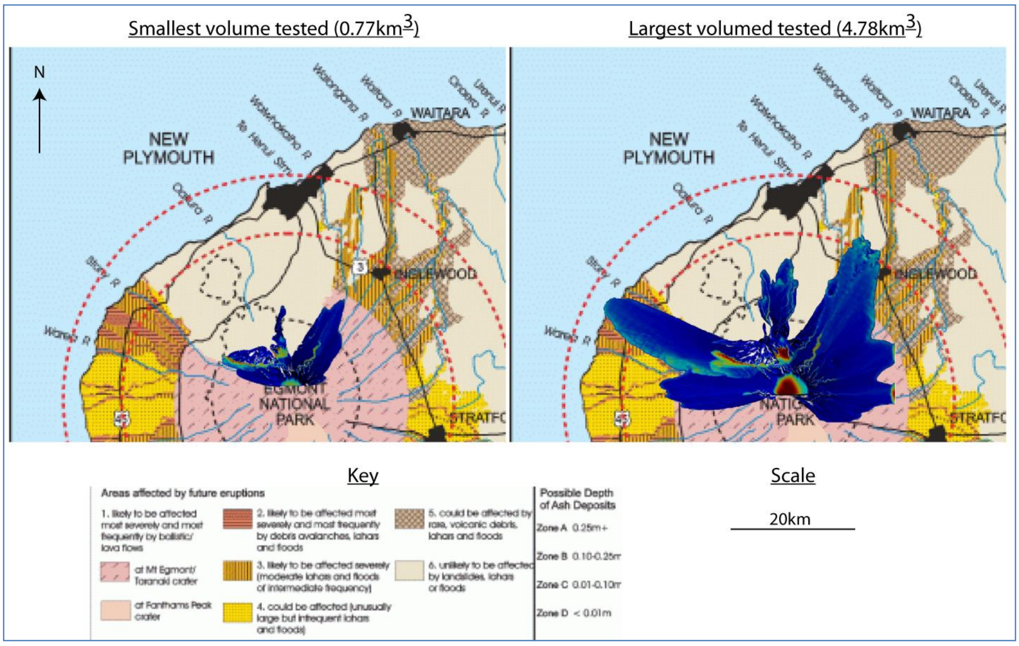


Figure 88. Geological Hazards map of the northern Taranaki region with the smallest and largest debris avalanches tested with *VolcFlow* (modified from Taranaki Regional Council, 2004)

The first observation is that whatever the volume used for the simulation is, the city of New Plymouth is not affected because the natural barrier (Pouakai range) stops most of the avalanche and diverts the rest. However some other towns such as Inglewood are affected by the deposit, as well as a good proportion of the New Plymouth district. The Pouakai range does protect the northern part of the Taranaki region (most of New Plymouth district) but it has some limits. In each simulation a small percentage of the avalanche overtopped the central part of the range to travel towards the city. So the area mapped as unlikely to be affected by avalanches on the geological hazards map is in fact likely to be affected, as even a volume smaller than 1 km^3 entered this area (Fig.88).

The second observation is that the deposit has a lobate shape because of the presence of an obstacle. All these results are coherent with the analogue modeling for this research (chapter

III) since the presence of an obstacle on the slope gave the same deposit shape category: lobate.

III. Conclusions

III.1. Impact of a debris avalanche on the north flank of Taranaki volcano

The simulations of debris avalanches on the north flank of Mount Taranaki gave interesting outcomes, with some limitations. The main result was the fact that the Pouaki does not completely stop the avalanche from heading towards New Plymouth, even for a volume of 0.77km^3. This changes the area at risk around the range but does not threat the city of New Plymouth. The second outcome was the shape of the deposit, which according to the previous analogue modelling study tends to have a lobate shape. The main modification of the volume is the area affected by the avalanche. The larger the avalanche, the longer the runout and the larger the area covered by the avalanche. However the same three main directions of the flow were observed in all cases.

III.2. Implication on the actual area

From a hazard management point of view, these results slightly reassess the evacuation plan as one area which has never been considered to be possibly affected by debris avalanche appears to be impacted by it.

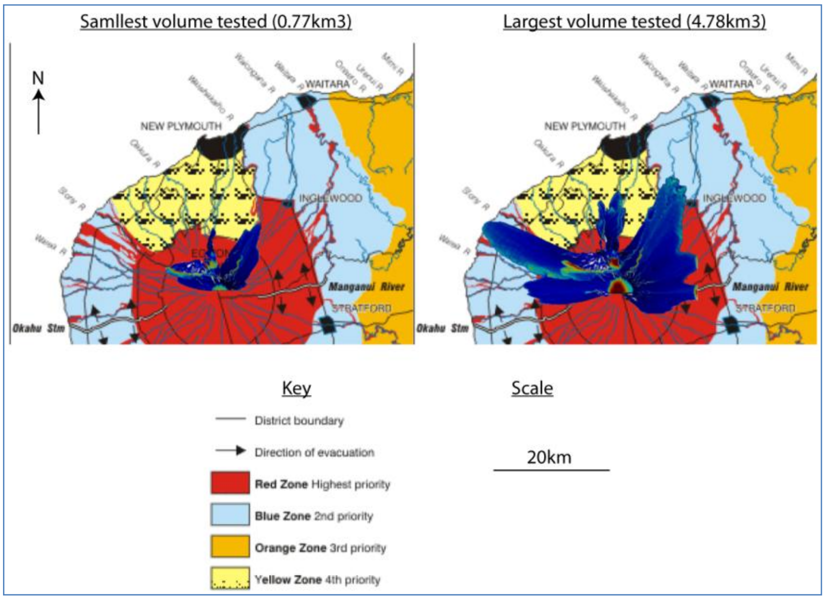


Figure 89. Evacuation map of the northern Taranaki region with the smallest and largest debris avalanches simulated (modified from Taranaki Regional Council)

The simulations clearly show a lobe of the deposit into the yellow zone, which is supposed to be the last zone to be evacuated in case of a volcanic event (Fig.89). It seems that some more studies should be done to test the outcomes of this research by using more detailed and precise data in order to redefine the priority evacuation zone.

Conclusions

This research has been carried out in order to improve the understanding of some aspects of volcanic debris avalanches, in particular the impact/effect of three variables: the volume of material involved, the fall height and the topography. To do so, statistical analyses have been carried out as well as analogue and numerical modelling.

I. Statistical Analyses: a useful tool

Any data can be analysed statistically, however to improve the accuracy of the analyses several steps need to be carefully followed before carrying out the analyses:

- Collect the data: the process was simplified by the use of the database created by Dufresne (2009). However that database has been complemented by the use of papers, reports and Ph.D theses on volcanic debris avalanches.
- Create the database: this is an important step as it determines how easily the database can be read, understood and used. The final database of this study is comprises 298 different debris avalanche deposits scattered all around the world and from different periods.
- Select the data: this is a crucial step in the analyses of the data as it can either increase or limit data errors or even confuse the results.

Two different types of statistical analyses have been carried out for this study: two-variable analyses and multiple-variable analyses (Principle Components Analyses, Regression). These analyses, have highlighted several trends. First of all, the fact that the influence of the fall height and the volume of material involved on the deposits depend on the volume of the avalanche. It has been shown that the runout and the volume have a better positive correlation when large debris avalanches are considered and that the H/L ratio is negatively related to the volume for medium debris avalanches. The fall height has more influence on smaller debris avalanches whereas the volume has more effect on medium and large debris avalanches. The influence of the volume is greater for a confined than an unconfined environment. It has been shown that there is no link between the initial and final slope angles. However one of the new outcomes of this study is the fact that the final slope angle is related to the debris avalanche deposits, since H/L ratio and α_2 are positively correlated regardless of topography. The bigger the mobility, the bigger the runout and the lower the deposit slope angle. The importance of $S/V^{2/3}$ ratio was pointed out by it link with the mobility of the debris avalanche (H/L ratio). The last factor is the influence of the topography, which has been characterised by the degree of confinement reported in the literature. Its impact is mainly on the geometrical characteristics of the deposit, especially the planform shape; however it also has a small influence on the runout; an increase in the degree of confinement gives an increase of the runout.

From all these results, two categories of behaviour have been determined regarding the relations between the parameters and their correlation. The first category is composed of small debris avalanches and of unconfined environments; whereas the second category is represented by medium debris avalanches and confined environments.

However these results have to be considered carefully as the parameters depend on how they have been measured in the field, how well the deposits are preserved and how well the pre-avalanche topography is known. And further analyses need to be completed in order to have a better understanding of the new relations pointed out by this research.

II. Analogue modelling

The second approach of this study was to test and quantify the trends found with the statistical study. The model used to reproduce a granular mass flow moving down a solid slope under gravity was developed and used for the first time by Shea (2005). This model, made of flexible aluminium sheet, simulates a gradual change in the angle of the slope and allows easy changes of parameters (drop height, slope angles, morphology of the environment). The material used to represent a debris avalanche was a sand mixture with a grain size between 100 and 600µm and different grain shapes. To this sand was added 10% plaster. Several experiments were carried out to test three different volumes of material, three different fall height and six different morphologies of the environment. In order to assess experimental errors, each experiment was repeated twice.

The results were accurate enough to show no scattered on a graph and to follow expected behaviours. For example, an increase of the volume gives a decrease of H/L ratio. This observation was complemented by the fact that H/L ratios are more sensitive to fall height with smaller volumes, but are always most sensitive to volume. For example, an increase of 230% in the fall height increases the runout by 20% whereas an increase of 90% in the volume gives a 30% increase of the runout. A similar result was obtained with the statistical analysis. An increase of either the volume or the fall height implies an increase in length, width & thickness. However, the thickness decreases if the fall height is increased. The impact of the topography is mainly on geometrical characteristics rather than on runout; however, an increase in confinement causes a slight increase in runout and the presence of an obstacle decreases the runout slightly. The shape of the deposit depends on the topography. An unconfined or regular confined environment tends to give an elongate deposit whereas a semi-confined environment creates a more or less accentuated fan-shaped deposit. However an obstacle causes a lobate deposit whose planform depends on the shape and relative size of the obstacle. The impact of the topography is largely influenced by the ratio of the size of the obstacle to the volume of material involved. The bigger this ratio, the more the avalanche is affected the by the topography.

III. Comparison of statistical and analogue modelling results

Here we look for any similarities and differences between the statistical and analogue modelling results. When plotting the results on the same graphic both sets of data follow linear tends regardless of the morphology of the environment. Thus the same processes occur in the field and in the laboratory. This observation is confirmed by the fact that the different data sets indicate similar behaviour of the debris avalanche in response to variation of the volume, fall height and topography.

IV. Importance of numerical modelling

The final aspect of this research was to test a numerical model ("*VolcFlow*"; Kelfoun and Druitt, 2006; Kelfoun et al., 2008) to determine how accurate this model is in reproducing experimental data. It was found that if the correct input parameters are used then any experiment can be successfully represented with this numerical code. The simulations demonstrated the similarity with the analogue modelling results (behaviour resulting from an obstacle). However the main result of the field test of Volcflow to simulate a large failure from the north flank of Mt Taranaki is that one zone that is presently considered unlikely to be affected by a debris avalanche is, as modelled, able to be affected. This requires further study, but the Pouaki range does not provided 100% protection from debris avalanche and a small event (0.77 km^3) can overtop the Pouaki range and affect the zone between the range and New Plymouth.

However some important questions remain; for example, can the Pouaki range itself collapse as a result of seismic shaking? What happens if there is a debris avalanche from Taranaki after the collapse of the Pouaki range?

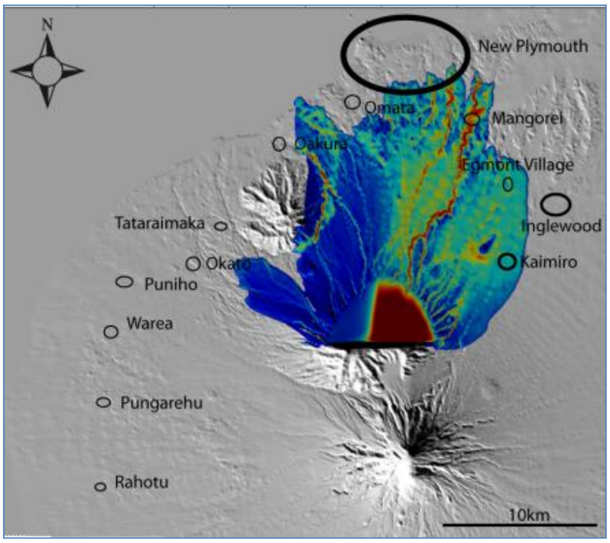


Figure 90. Simulation of the Pouaki range collapse using *VolcFlow*

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Appendix

On the CD

I. Database

II. Statistical analyses

II.1. EXCEL

II.2. PCA

II.3. Regression

III. Modelling

III.1. Analogue

III.1.1. Pictures & movies

III.1.2. Data

III.2. Numerical

III.2.1. Environment 1

III.2.2. Environment 2

III.2.3. Environment 3

III.2.4. Environment 4

III.2.5. Environment 6

IV. Case study

IV.1. V=0.77km^3

IV.2. V=2.19km^3

IV.3. V=3.67km^3

IV.4. V=4.78km^3